A SMART GRID BASED ON A THREE PORT ENERGY TRANSFER COMPONENT

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted to the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

D Visagie (399781)
06 (Sixth) day of August year 2013

ABSTRACT

As the demand for electricity increases worldwide on mostly constrained networks, Smart grids pose an alternative solution to conventional generation. Previous work on Smart grids is discussed in this dissertation and it is highlighted that future Smart grids should not only address peak demand, but also stimulate the use of distributed renewable energy sources and promote interaction between customers and the utility.

A solution to the above three requirements in the form of a novel 'T'-Smart grid comprising of a fundamental Control-component and 'T'-components is presented. It can seamlessly and intelligently integrate a large number of distributed energy sources and energy storage devices. The 'T'-Smart grid can also ensure complete protection between all the Grid-components (sources, loads and energy storage elements) by the use of a novel Fault Current Limiter (FCL). The FCL not only limits fault current amplitudes and negates fault current propagation throughout the grid, it also transforms the grid into discrete states which allows the 'T'-Smart grid to assess, manage and control any network condition in an optimal way as this system makes information about the available energy and load requests known upfront.

Several financial incentives and hardware solutions to reduce peak demand or ensure a flatter energy consumption profile are also proposed and discussed.

The financial solutions consist of charging customers for exact shared network usage, for events where external grids are required to assist with energy or where other loads had to be shed to meet the demand, as well as a network demand charge.

Possible hardware solutions include the 'T'-Smart grid's unique ability to intelligently manage energy storage elements in three different modes of operation.

The proposed 'T'-Smart grid is developed and tested within a simulation environment and it is then shown and concluded that the three requirements mentioned earlier are met. It is also concluded that the 'T'-Smart grid, its components, properties, grid management rules, models and test simulation results make it a possible future Smart grid solution.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADMS	Advance DMS
AMI	Advance Metering Infrastructure
CT	Current Transformer
DC	Direct Current
DMS	Demand Management Systems
DOE	(American / United States) Department Of Energy
FCL	Fault Current Limiter
LM/LE	Load Modelling / Load Estimation
N/O	Normally Open
PLD	Percentage Level Discharge
RMS	Root Mean Square
SCADA	Supervisory Control And Data Acquisition
SNC	Shared Network Costs
SOC	State Owned Company
VAR	Voltage-Ampere Reactive
VT	Voltage Transformer

CHAPTER 1: INTRODUCTION TO THE DISSERTATION

1.1 INTRODUCTION

This chapter is a brief overview of the background, problem statement and the need for a future Smart grid. It also details the requirements to be met by the dissertation, in the form of a proposed Smart grid solution which is theoretically defined, designed and then created in a simulated environment for testing and concluding whether it could be beneficial to the future Smart grids. The chapter is concluded with the high level details of the chapters to follow.

1.2 BACKGROUND AND PROBLEM STATEMENT

The increased demand for electricity worldwide necessitates the need for more conventional power generation stations. These conventional generation stations require large financial investment, space, political will and have an environmental impact. In many cases one or more of these factors cannot be met or addressed and an alternative to conventional generation is required.

The current trend is the Smart grid concept and it embodies a range of hardware, software, legislative and other means to address the increase in electricity demand.

While exploring solutions to the problem, it has been realised that grids worldwide are generally old, utilised to their limit, large and overly complex, and need to be utilised while the new Smart grid is implemented, or it must form part of it.

Further investigation into Smart grid solutions identified that a large number of customers make use of electricity in a common time period, leading to a system peak. This system peak can usually not be met by existing generation capacity or network infrastructure. At least two solutions to this immediate problem have been identified namely making use of an Advance Metering Infrastructure (AMI) or a distributed energy storage system.

An AMI system in its most basic form is a concept whereby the customer either pays more for electricity in known peak demand periods or the actual grid demand is communicated in real-time to customers so that the electricity price increases proportionally with the demand on the grid. This then causes the customer to either manually move electric loads to lower demand periods or implement automated systems that know their preferences, such that electricity is used in periods constrained to a preferred maximum cost, and so adapt around the constraints of the grid.

Distributed energy storage is aimed at storing energy mechanically, chemically, electro-statically or other means and to place it at strategic locations in the network. These units can then charge energy in low peak periods and then discharge energy in high peak periods. (Other proposals have also been made to transport stored energy from places in the grid experiencing a low peak demand to locations experiencing high peak demand.)

Both proposed solutions are considered worldwide. In the author's opinion, these solutions, considered in isolation will reach a limit whereby it cannot further address future energy demand requirements, environmental requirements, or assist in improving communication and interaction between the utility and the customer.

Also note that the trend to use more renewable energy generation in a decentralised configuration (to limit network constraints) is also not fully addressed. The use of renewable energy generation not only relieves the dependency on deplete-able oil / coal (fossil) material but also address the need to reduce green-house gasses that lead to global warming.

A solution to all these problems and constraints are required and the American Department of Energy (DOE) released a document [1] to state what it believes to be the most important aspects of a future Smart grid. First and foremost, the current grid which is producer controlled and has centralised generation needs to transform into a consumer-interactive network with distributed generation to ensure economic and environmental sustainability. In addition, the future Smart grid must have the following properties [1]:

- ✓ Intelligence
- ✓ Efficiency
- ✓ Accommodation of different types of sources
- ✓ Motivating communication between consumer and utility
- ✓ Opportunistic (new opportunities and markets)
- ✓ Quality Focussed (Power Quality)
- ✓ Resilient, against attack
- ✓ "Green", reducing global climate change.

Furthermore the technologies that are expected to drive the final Smart grid solution would have the following properties and abilities [1]:

- ✓ Integrated Communication
- ✓ Sensing and Measurement Technologies
- ✓ Advanced Components
- ✓ Advanced Control Methods
- ✓ Improved Interfaces.

In [1] it goes on further to indicate that once all these technologies, techniques and tools are applied a Smart grid would be developed that [1]:

- ✓ Ensures grid reliability to a level never experienced before,
- ✓ Maintains its affordability,
- ✓ Reinforces global competitiveness,
- ✓ Has the ability to fully accommodate both traditional and renewable energy sources,
- ✓ The potential to reduce carbon emissions,
- ✓ Enable advancements in efficiency.

The problem statement of the work is to develop a Smart grid system; one which is able to assist in addressing the peak demand problem, support the use of distributed sources, loads and energy storage systems that can be integrated seamlessly, and to promote and provide a platform for improved interaction between the utility and the customers.

1.3 SCOPE AND OBJECTIVES

The scope of the dissertation is to develop a solution to the problem previously stated. The solution must then be implemented and be subjected to various network configurations and situations to demonstrate its functionality and means to meet future Smart grid requirements.

The secondary objective is then to study the proposed Smart grid solution (called the 'T'-Smart grid) further and determine whether it could aid future Smart grid development or not.

1.4 DESIGN METHODOLOGY AND DELIVERABLES OF THE DOCUMENT

The design methodology is to engineer, develop and test the proposed Smart grid solution (called the 'T'-Smart grid) in a simulated environment using Matlab (Simulink).

The deliverables of the document will then be the proposed concept in theoretical format, its equivalent simulated models and the tests performed on it to conclude whether it address the problem statement or not.

1.5 OVERVIEW OF THE DOCUMENT

This document can be divided into two main sections. The first two chapters (Chapter 1 and Chapter 2) detail possible future technologies and constraints surrounding Smart grids. Some important proposed Smart grid solutions that were developed by others are also discussed and key features of them are recorded and used in this dissertation's proposed solution.

The second section (Chapter 3 to Chapter 5) details the proposed 'T'-Smart grid solution from its concept idea, to implementation in a simulated environment and testing, and final discussion of results and outcome.

In the final chapter (Chapter 6) it is discussed and concluded whether the proposed 'T'-Smart grid of this dissertation met the requirements of the problems statement.

CHAPTER 2: DISTRIBUTED GENERATION, STORAGE, DEMAND MANGEMENT TECHNOLGIES AND POSSIBLE SMART GRID SOLUTIONS

2.1 INTRODUCTION

The increase in demand for electricity currently leads to an increased use of non-renewable resources and expansion of existing infrastructure. In future, the use of renewable sources will become more prevalent due to the effect of greenhouse gasses and climate change caused by non-renewable sources. [2] Various viable renewable technologies (such as photovoltaic and wind) are piloted all around the world [2] and the local utility has allowed Independent Power Producers to connect to the grid as well. Energy storage technologies used to reduce the peak demand are also well understood and can be considered as part of the future Smart grid to reduce peak demand, instead of infrastructure upgrades which can be costly and time consuming [2].

Furthermore, several Smart grid technologies are currently being researched and implemented. These technologies must not only reduce peak demand and better utilise existing infrastructure, but must also have significant operational benefits to the utility and the end-customer. However, all these technologies still need to be properly integrated and then adapted to allow for distributed renewable energy and smart electricity consumption by the end-customer. This technology, referred to as Distribution Management Systems (DMS) and its possible future improvement, Advance Distribution Management Systems (ADMS) will be described in this chapter. [4]

However, in the future even more complex Smart grid solutions will have to be implemented to meet the demand. That is, functions that can reduce capacity constraints even further after ADMS functions have been considered. Two such Smart grid solutions are briefly explained in this chapter.

The first solution will describe an intelligent local controller which manages the grid and ensures customer-configured preferences are met, while still maintaining a high standard of power quality and reliability. This is achieved through optimal management of storage sources, local generation, responsive loads and standby electric services in the supply system while ensuring adequate communication about the grid’s status to the customers. Hence, the local controller makes optimized decisions locally (in a micro-grid), while taking into consideration the entire grid. A local controller will also consider environmental, economic, comfort and other related objectives including regulatory and physical constraints in order to enhance the day-to-day electricity consumption, to be more effective and efficient. [5]

The second solution describes an energy internet solution where the future Smart grid is compared and adapted to have the same flexibility and features as what the existing internet has. The basic solution entails an energy internet where supply flows similar to data packets, from the supplier to the customer. Benefits of this include reliability, robustness and openness. [6]

All this information will be used to develop a Smart grid platform in Chapter 3 to Chapter 5, which should be able to support such devices and applications in future.

Note that the intention of this chapter is not to add to these technologies, but to alert the reader of their existence and to ensure that the Smart grid proposed in Chapter 3 to Chapter 5 can provide a suitable physical platform for these types of applications to be implemented.

2.2 RENEWABLE ENERGY GENERATION

Some of the future renewable energy generation that would become more prevalent and connected to the future grid include [3]:

- ✓ **Tidal Power**, which captures water from high-tide inflow and stores it in dams.
- ✓ **Wave Power**, that takes advantage of the fall and rise of a water level.
- ✓ **Nuclear Power**, of which the nuclear waste is recycled.
- ✓ **Wind Power,** that makes use of kinetic energy produced by wind.
- ✓ **Geothermal**, which extracts energy in the form of heat from the inner core of the earth.
- ✓ **Hydropower**, which is energy generated from either a river or water stored in a dam.
- ✓ **Landfill Gas**, that harnesses methane gas (as energy source) from commercial and household waste.
- ✓ **Solar Energy - Photovoltaic**, which generates electricity directly from sunlight.
- ✓ **Solar Energy - Concentrated Solar Power**, that uses large mirrors to actively track and focuses the sun's energy to produce hot gas or steam.

Each has its advantages and disadvantages and it would require significant financial support, political will, and consideration to the environment to determine the best possible solution (or hybrid solution) for a specific area to meet the energy requirements. [3]

In South Africa, the local utility has invested in a demonstration plant that would determine whether molten salt-type (Concentrated Solar Power) central receiver technology is a viable solution in the region. This plant will also be equipped with energy storage capabilities.

In addition, the local utility has also invested in another demonstration plant to determine whether Underground Coal Gasification can be an option for a base load power station which can compete with traditional coal and nuclear plants in terms of plant lifespan, cost and environmental considerations.

2.3 ENERGY STORAGE

Storing energy in low peak demand periods, to release it in high peak demand periods can also relieve the need for infrastructure upgrades. Some of these technologies, which can be expected to be connected to the future grid include:

- ✓ **Pumped (Hydro) Storage Schemes**, which stores water in dams (or caverns) at elevated levels during low peak demand time, such that it can be released during high peak demand times to a lower dam. Energy is thus stored in the earth's gravitational field as potential energy [3].

- ✓ **Flywheel storage**, which stores energy kinetically [3].
- ✓ **Battery Storage**, which stores energy chemically. This solution can also be extended to be included into automobiles, such that it serves as a means of transporting energy closer to the demand. Example: Plug-in Hybrid Electric Vehicles. [3]
- ✓ **Fuel Cells**, whereby energy is stored and released by means of a chemical reaction between hydrogen and oxygen. The reaction generates water, heat and electricity [3].

Combining energy storage with renewable energy allows for a consistent stable supply of energy to the local grid and enables it to compete with non-renewable base power plants [3]. Also, recent IEEE white papers are considering connecting hybrid cars, running on Bio-fuels, to a regional-transmission grid as another form of distributed generation and storage combined. [2]

2.4 Modern Distribution Management Systems (DMS)

Although many DMS technologies stem from extensions to the Supervisory Control and Data Acquisition (SCADA) system, the distribution system did not evolve to the same extent as these technologies that were implemented on the transmission and generation systems. [4, 8]

There is an interest in Smart grid technologies that would postpone infrastructure upgrades and build-outs, reducing maintenance and operating cost (through the improvement of the current grid's efficiency), and increasing the reliability of the network and enabling the enhanced management of current assets. [4, 8]

Some available DMS Smart grid solutions to assist with this are briefly explained below [4]:

- ✓ **Fault Detection, Isolation and service Restoration** - A system that automatically senses and sectionalises faulty sections of a network, restores supply where possible, and thus increases system reliability.
- ✓ **Integrated Voltage/VAR Control** - The system controls energy levels in capacitor banks (to reduce feeder losses) and ensures an optimal voltage profile along a feeder by means of controlling transformer tap positions and voltage regulators, to reduce peak loading.
- ✓ **Topology Processor** - The system is an offline application that accurately determines the optimum topology of the distribution network and can also suppress unnecessary alarms caused by network topology changes.
- ✓ **Distribution Power Flow** - Solves unbalanced three-phase load flow problems in distribution networks connected in radial or meshed formation.
- ✓ **Load Modelling / Load Estimation (LM/LE)** - This function dynamically forecasts both individual loads and bulk loads in the distribution grid, based on available information which may include transformer loading, customers' bills and measurements along feeders. This then allows Grid-operators to better manage generation resources.

- ✓ **Optimal Network Reconfiguration** - The system proposes different reconfigured networks to minimize network losses, uphold the optimum voltage profile, and to balance loading amongst the network phases, distribution feeders and the substation transformers. This application can also develop outage plans, for when work is to be performed on the network.
- ✓ **Contingency Analysis** - Through analysing possible switching and fault scenarios that can adversely affect the customer's supply or operational safety of the network, the system changes the network configuration to ensure maximum reliability and minimum customer outages.
- ✓ **Switching Order Management** - After many of the DMS applications have produced switching plans to reconfigure the network, this application will then assess all the plans through advance control analysis to optimise the switching operations and will also be responsible for verifying, executing or rejecting such plans.
- ✓ **Short Circuit Analysis** - This off-line application calculates the short-circuit current for a theoretical fault in the network, to determine the impact it may have on the network and then verifies or adjusts protection relay settings to be more precise such that it would reduce network impact and can also recommend a different network configuration to alleviate the problem.
- ✓ **Relay Protection Coordination** - The application actively verifies and manages relay settings for distribution feeders, as different operating conditions and reconfigurations in the network occur.
- ✓ **Optimal Capacitor Placement / Optimal Voltage regulator Placement** - This offline application determines the optimal placement of voltage regulators and capacitor banks in the distribution network to ensure cost effective control of the feeder's voltage profile and VARs. Hence, the feeders can be used more optimally.
- ✓ **Dispatcher Training Simulator** - This application simulates effects caused by abnormal and normal switching scenarios and operating conditions before it is executed on the real system. The application can also be used to simulate historical operating conditions and possible future network expansion conditions and thus allows Grid-operators to evaluate the effects in advance of a given operation plan.

As previously mentioned, the future Smart grid will have to reduce costs and ensure that spare capacity is made available from the existing infrastructure. This can be achieved through monitoring of the grid and control by DMS applications. [4]

In future, one can also expect residential loads to become automated from an electrical perspective. Such a system would not only manage residential loads but also manage [4]:

- ✓ **Renewable sources -** For electricity supply directly to the customer.
- ✓ **Plug-in Hybrid Vehicles** - That store and transport electricity.
- ✓ **Smart lighting** - That only adds light to the existing light levels.
- ✓ **Intelligent appliances -** Which can take the grid's demand into account before using the electricity.

Furthermore, it can be expected in future that the entire distribution, transmission and generation network will be automated (in terms of control) and renewable sources would be able to be integrated at any point in this network. [4]

Although DMS technologies aim to reduce the grid's peak demand, once distributed renewable sources are added to the grid, it would be difficult to predict when supply is available and for what period. Customers will also manually adapt their loading habits to benefit from tariff or economic incentives, rather than following a fixed pattern [5]. Because of this, the previous mentioned LM/LE application which is responsible for predicting the load will become inaccurate. Furthermore, as the LM/LE application output is as input to many DMS applications, the DMS application will also become less effective. [4]

ADMS applications are designed not be affected by this problem and will have access to real-time network data, pricing and reward policies governing customer loads, to better predict load flow and to match it to available energy. [4]

Some ADMS applications are briefly explained below [4]:

- ✓ **Advance Control, Monitoring and Data Acquisition** - Whereby control and monitoring functions across the network extend to the last element level, before connection with the customer. (Example: Mini-substation or Pole-mount transformer.) In some cases, it might also be integrated with AMI or home energy management systems.
- ✓ **Open Interfaces, Standards, Integrations and systems** - This will allow advance applications to be added and integrated into the system. Open data exchange interfaces and open standard databases will then also permit and have the agility to accommodate utility required applications without having a forced monolithic distribution management system.
- ✓ **Optimisation of the DMS application: Fault Detection, Isolation and service Restoration** - To enable it to function in parallel, closed-loop and radial configurations. It can also have other additional features such as multi objective restoration strategies, multilevel feeder reconfigurations, and predictive network loading validation.
- ✓ **Asset and operational improvements of the DMS application: Integrated Voltage / VAR Control** - Which will enable it to detect failed capacitor banks, keep record of the tap changer actions, status of the capacitor banks and operations of regulators that are later used for optimal component placement and cost-based optimization.
- ✓ **An adapted LM/LE DMS application** - where load behaviour of customers are not predictable, but intelligently managed individually.
- ✓ **Increased complexity and increased frequency of use for the DMS applications: Distribution Power Flow, Topology Processor, Contingency Analysis, Optimal Network Reconfiguration, Relay Protection Coordination and Short Circuit Analysis** - Systems will also be adapted for service at individual customer level.
- ✓ **ADMS linked to geographical databases** - Whereby geographical databases are integrated with network data and physical location of components.
- ✓ **Tracking tools** - That records changes to control / instrumentation panels and general historical data and compiles reports to assess the performance of Smart grid initiatives in the distribution network.
- ✓ **Advance filtering and analyses tools coupled with visualisation** - Data from field devices can then be integrated with other applications and can then give a clear overview of a substantial amount of data in a visual format.

- ✓ **Integration with enterprise components** - This is a key feature to ensure the success of other applications such as AMI.
- ✓ **Security improvements** - To guarantee secure communication between applications, field devices and customers.

The previous mentioned ADMS functions are currently being developed and tested overseas while the South African electricity utility is busy conducting a pilot project to research and implement a phase-shifting transformer that is able to re-direct real power flow to alleviate network constraints. This would then solve the need for network expansion where the acquiring of servitudes can take time or where investment into network upgrades is too expensive.

2.5 A LOCAL CONTROLLER SOLUTION

A possible Smart Grid solution (beyond ADMS solutions) could entail a controller responsible for increasing reliability and service quality at customer level. To achieve this, it must take into consideration commercial information and parameters, customer preferences, utility tariffs and rules, and alternative supply source prices. This information will be vital in establishing intelligent coordination between distributed resources especially in a competitive environment. [5, 9]

Prior work by many researchers has already determined the technological components and function needed for the local controller to be able to perform Smart grid operations in terms of this described concept. Amongst the components, the "slave controllers" are responsible for managing local distributed resources, namely [5]:

- ✓ **Distributed generation**
- ✓ **Energy Storage**
- ✓ **Responsive loads**
- ✓ **Smart switch controls**

The local controller uses these components in a coordinated fashion to ensure continuous supply of critical loads while still operating these local devices (generation, storage and responsive loads) in an economical way. [5, 9]

The local controller thus communicates through various interfaces with all the Grid-components and information sources. Some of these are described below [5]:

- ✓ **Supply System and Market Interface -** This interfaces between the local grid (supplied by the main-grid) and commercial markets.
- ✓ **Local Generator and Storage Device Interface -** This optimally coordinates storage and local generation operations based on considerations of the local electricity usage, external supply conditions and market conditions.
- ✓ **Load Control Interface -** Several exist and include energy management systems and load control devices retrofitted to end-use equipment. These interfaces control loads as electricity prices, local generation, supply conditions or local usage vary.

- ✓ **Fast Switch (Solid State breaker) -** This switch isolates the local grid from its supply, when a fault occurred. (The solid state breaker can switch considerably quicker than a conventional breaker and thus reduces the impact of the fault on the grid significantly.) This interface will then manage reconnection based on information regarding the supply, electricity usage, and local generation as well.

Such a Controller must also be able to handle many scenarios (that it would encounter), from which one can later deduce its functional requirements. Some of these scenarios include [5]:

- ✓ Responding to an emergency grid state.
- ✓ Responding to dynamic price changes.
- ✓ Selling of services to a supply system.
- ✓ Taking into consideration environmental values of operations.
- ✓ Forecasting local generation and load profiles.
- ✓ Determining and execution of a day-ahead operations plan.
- ✓ Responding to disturbances in the supply system.
- ✓ Enabling the grid operator to make changes to default settings.
- ✓ Responding to local grid contingencies, such as the loss of a local generator.
- ✓ Operating while connected to grid.
- ✓ Operating while isolated from grid.
- ✓ Operation under loss of data or communication.
- ✓ Black start.
- ✓ Operating while connected to the grid, with black start.
- ✓ Islanded operation, with black start.

From this, the high-level functional requirements of such a Local Controller can be deduced and some of them are briefly explained below:

- ✓ **Information processing** - This is an important aspect that supports decision-making processes. Inputs are gathered from interfacing with commercial markets, grid resources and customers. Information on environmental conditions can also be combined an optimized through this function. [5]

  Many information functions exist, but the core functions that should support the controller under operational conditions include [5]:

  - A demand response function under emergency conditions,
  - A dynamic price response function and
  - A demand bidding function when power supply is sold to the grid [10].

  With the help of these functions, a broad range of services from distributed resources can be connected and utilised by the grid which include [5]:

  - Ancillary services which is sold to the electricity market,
  - Voltage regulation to support the grid and
  - Demand response in-line with emergency and economic conditions.

- ✓ **Forecasting the price of Electricity** - This function can forecast the electricity price, based on the models and information sources the user has chosen. Such models may take into consideration market prices, transmission congestions and even weather conditions. [5]
- ✓ **Dynamic Price Processor** - The function of this processor is only to relay price signal inputs to the relevant local controller functions and Grid-components. The functions that require its output (information) includes the calculator (which determines the cost of electricity), the forecaster (which forecasts the electricity price) and functions that optimize based on economic considerations. [5]
- ✓ **Electricity Cost Calculator** - The function takes into account actual measured values and electricity retail prices and determines estimates of the electricity cost for pre-defined user selected intervals such as per day, hour, etc. This function derives the retail prices from the retail tariff structure which can be a dynamic priced system in itself. [5]
- ✓ **Forecasting Electricity Costs** - This function forecasts (unlike the calculator) projected electricity costs based on scheduled or forecasted usage. The forecasted costs will also be dependent on the relevant retail tariff structure which again can be dynamic. [5]
- ✓ **Assessment of Demand Bid Opportunities** - The purpose of this function is to scan the market and grid conditions to determine if there are opportunities in the demand-side market for a given time, price and quantity of electricity. The function must also be able to determine alternative bid opportunities from market configured opportunities. [5, 10]
- ✓ **Demand Bid Submission** - The intention of this function is to order, package, and submit a bid, together with the type and identification of the resources involved in the bid, to the system. Packaged data may include targeted market opportunities, quantities, bid prices and other services that can be sold. [5, 10]
- ✓ **Acknowledgement of Bid Awards** - Once a successful bid is received from the supply system; this function must process and notify the local controller as well as the receipt thereof by the controller back to the supply system of this event. [5]
- ✓ **Local Grid Resource Updater** - This function is tasked to keep the system updated about the availability of the local grid resources based on information gathered from slave controllers and the known characterises of the resources (which is also dependant on the configuration). This information is continuously collected, processed and combined to give an overview of the external supply system. [5]
- ✓ **Resource Deployment Scheduler for the Local grid** - This function is in control of determining the schedule for the deployment of individual local resources. These schedules are optimized in accordance with market opportunities, end-use priorities and predefined optimization functions. [5]
- ✓ **Resource Dispatch for the Local Grid** - The purpose of this function is to communicate control signals or schedules to the individual resources in the local grid. [5]
- ✓ **Presentation of Information** - This function is responsible for presenting the user required information and can be through a web-based interface. [5]

The South African electricity utility has already started to implement (and patent) a Utility Load Manager system that sheds specific customer loads (such as geysers) in real-time, when the system is experiencing capacity constraints. It is estimated that up to 4000 MW of capacity can be made available if implemented nationally. Unlike the Local controller, this does not take into consideration customer preferences, and it is controlled centrally and not locally. However, it does provide a platform for other technologies to evolve from it, such as the local controller concept.

Note that all these functions give an insight into the complexity and communication needs of such a controller. It is thus evident that a Smart grid of the future will have to be able to effectively communication with many information sources, Grid-components and customers, in order to ensure an optimized management of the grid.

2.6 AN ENERGY INTERNET SOLUTION

Another possible Smart grid solution is as an energy internet where supply flows similar to data packets, from the supplier to the customer. Benefits of this include reliability, robustness and openness. [6, 7]

Usually resources are centralised and customers (or loads) are distributed. This requires a sophisticated distribution and transmission network that meets demand at any given position or time in the network. In this network, reliability and efficiency can be considered as important properties, but even with a focus on reliability, it cannot be guaranteed that the network will also perform without defect. [6, 7]

As previously mentioned, it can be expected in future that safety margins between generation capacity and demand will be even lower than what is currently experienced due to economic and environmental considerations. It is expected in future that an alternative solution named "generating through saving" would hopefully assist this tight margin. [6, 7] (This is almost similar to the Utility Load Manager system mentioned earlier.)

Note that a complex energy infrastructure is only in a stable and healthy state when its generation, transmission, distribution and customer networks are correctly configured. This in itself is a challenging and complex problem of optimization. Currently, the best possible means is to implement an intelligent / multi-agent where solutions are searched and investigated as opposed to explicitly formulated. Thus, an agent environment or framework is defined to allow interaction between components together with a few protocols to regulate the interaction. Effective agent environments and proper protocols allow components to adaptively reconfigure themselves in order to last in the system. Then, the system would acquire a self-healing ability which is very desirable. Thus, whenever the system is not operating in its optimal point or configuration, components will correct this by automatically reconfiguring themselves. [6, 7] (A local controller can be considered as one such agent solution.) The Internet can be considered as an example which has all these characteristics. Therefore, an Internet-type network is advantageous and considered as a next generation solution to the energy infrastructure. This new system presents a unique and unparalleled ability in terms of flexibility to service providers, users, regulators and marketers. [6, 7]

Improvements made in general to Smart grids have led to the reinvestigation of a full scale and complete energy internet by many researchers. It was found that construction of such a network requires considerable effort and inputs from diverse sectors including social science, technology, and legislation. Although the Internet is a fully developed technology, key differences between electrical energy (in vast quantities) and electrical data exist. A direct copy of this technology is thus not possible. The reasons for this are listed below [6]:

- ✓ When compared with electrical data, electrical energy is currently being centrally generated and locally consumed unlike data. Transmission over long distance are extremely critical and control thereof becomes very important considering that usually, only limited routing / supply options exist. Hence, the probability of a bottleneck, where capacity cannot meet demand, is more likely to occur.
- ✓ Unlike electrical data that can be stored and retransmitted in large quantities over the Internet, current technology has not solved this problem for electrical energy. Storage serves as a buffer in an involved system and is therefore a significant factor to consider. Conversely, the lack of storage will amount to vulnerabilities for numerous types of instabilities in the electric power grid.
- ✓ A "Best-Effort" model is used by the Internet, followed by 'Quality of Service' as a secondary consideration. This is however a direct opposite to the assumptions of an energy network. The main priority is to have the service network meet the customers' demand at any time. Consequently, the challenge for the Internet is to allocate bandwidth such that data packets will be delivered in an efficient manner. In contrast, in an energy network, the demand of customers must be carefully monitored and forecasted such that the generation, transmission and distribution network can be prepared to meet the demand which could occur at any given time.

It is important to recognize these key differences, in order to develop an energy internet. When considering all the possible solutions to deal with these differences, the anticipatory control approach seems to have the most potential. The anticipatory control system is made up of a set of tools that execute control actions determined by the system's projected state(s). This powerful concept is derived from the ineffectiveness of the conventional approach to act on current-state information. Anticipatory control has two main parts, the anticipation of future network states and then the intelligent decision-making process based on this. [6]

The following are key assumptions for the energy internet solution to be successful [6]:

- ✓ **Information being intelligently managed and shared will lead to virtual energy storage -**

  As mentioned previously, the biggest challenge of the energy internet is its inability to store large quantities of energy distributed within the network. Due to the fact that currently no adequate prospective technological solution exist, it has been argued by researches that this can still be virtually achieved through the intelligent management of information and sharing thereof. The concept is to virtually create an energy buffer between the supplier and the customer.

  This virtual buffer is realized through a Demand Side Management plan which is based on the practise of an actively data driven model. The materialization of intelligent meters has given the ability to actively schedule electricity consumption for each customer. It is this scheduling that will create a partial virtual buffer between the electricity consumption of the customer and generation. (Hence, the electricity consumption is predicted, then scheduled and then consumed by the customer. It is the period from when the energy is scheduled until it is consumed which creates a partial virtual buffer.)

The above mentioned model will allow the intelligent management of electricity consumption by each customer. Customers will however lose their ability to power up their equipment at will. Preferably, customers will take smart decisions with consideration to cost and benefits.

As an example, laundry and other non-urgent activities can be scheduled for during the day or night, when demand is low and consequently electricity is abundant and cheap. Electricity costs will be determined by the network capacity required to transfer the energy and the associated supply-to-demand ratio. Managing resources in such a way is similar to the access control generally used throughout the Internet. Thus, in this manner, a virtual buffer between the consumption and generation is created. The electricity is thus simply consumed when generated, through careful planning and estimation of when the consumption will take place. Though, from the customer's perspective, with active consumption scheduling the electricity is generated and then stored in the power grid before being consumed. It is also suggested that this virtual buffer can greatly improve the power grid's stability.

Intelligent or software agents will be responsible for active scheduling. These agents will represent their clients, ensuring reasonable decisions are made and taken (thus, executed on behalf of the client) based on analysis done for a given situation. The capability to anticipate is one of the most crucial analysis aspects that an agent should have. It is the task of the intelligent agent to predict future consumption of its client, and ensure that scheduling is possible. Thus, the most important function of such a system is load forecasting.

✓ **Effectively managing uncertainty through price elasticity -**

As discussed earlier, forecasting is one of the most important functions of an energy internet. Nonetheless, accuracy must be taken into consideration when using forecasted data as a basis for generation. Uncertainty never parts from predictions and millions of predictions all summed up may have an unacceptable high level of uncertainty. A second assumption is made to overcome this. That is, uncertainty can be effectively managed through price elasticity.

This assumption is equivalent to an assumption made in control systems about feedback. As reference, measurements that are fed back will assist the controller in regulating the output in an adaptive manner. For this reason, it is not required for the controller to be extremely accurate. Thus, an analogous conclusion can be reached here. Assume a feedback loop exists such that it connects consumers and suppliers together; then forecasted errors will be adaptively minimized (corrected) over time. Price elasticity is thus a favourable feedback mechanism of which short-term elasticity in particular, is the best. Estimates on the customer's willingness to purchase supply, while price changes occur, can only be achieved after the implementation of a proper short-term model for price elasticity. Using this tool, suppliers and customers can engage in dynamic negotiations to reach a careful balance between consumption and generation, even with a load forecast that is less accurate.

Numerous possibilities exist for the construction of an energy internet. However, several requirements, of which only the most important will be discussed, have to be met to make it successful. Such requirements include [6]:

- ✓ **Smart Meters with communication capabilities and unique addresses** - This will allow two-way interaction between customers and suppliers.
- ✓ **Capability to Forecast** - Anticipation and predictions are vital stabilizing factors in an intricate system such as a Smart grid. Research methods have shown that Nonparametric (neural networks), parametric (statistical) or even hybrid (fuzzy logic) techniques all have the ability to accurately predict the short-term demand for a given customer.
- ✓ **Multi-Resolution Agents** - Intelligent agents are required for the real time operation of an energy internet. These intelligent agents must act on behalf of the clients they represent. Clients can be actual customers, electricity brokers, Grid-operators or even equipment in the grid such as generators, transmission / distribution feeders or transformers. Intelligent agents must have sufficient knowledge to be able to act rationally.
- ✓ **Short-term price elasticity model** - Price elasticity characterises the sensitivity of the customer, with respect to change in price. For electricity, the price elasticity gives an indication of how a price change, can impact the customers' preferred power consumption. A good quality short-term price elasticity model will provide a foundation on which interactions between the suppliers and customers will take place.

The Smart grid energy internet solution has again highlighted the fact that the future Smart grid will require advance and robust communication infrastructure, to function effectively.

These concepts and ideas from the local controller and the energy internet were used to develop the 'T'-Smart grid mentioned in Chapter 3 to Chapter 5.

2.7 CONCLUSION

In future, it can be expected that distributed generation (which will mostly be renewable) will be connected to the grid, with or without energy storage capabilities. It can also be expected that these technologies will further developed in future, and that it would become mandatory to integrate these technologies into the Smart grid to lower peak demand.

Also, there are widely recognized DMS systems currently used by industry, but it expected not to function as effectively with the introduction of the Smart grid. The reason for this is that Load forecasting might become more difficult as customers react to price increases caused by network constraints (or even certain price polices) rather than a fixed pattern of consumption. Therefore, ADMS functions have been developed which rely on advance load prediction tools (which has access to the above information) and will be able to take these external factors into consideration and predict plus control the future Smart grid.

Using distributed renewable generation, energy storage devices, DMS and ADMS functions can lower peak demand in the grid, but might not realise the system reliability and customer requirements and satisfaction of a future Smart grid. Therefore, two proposed Smart grid solution which address these concerns where briefly discussed.

The first possible solution was a local controller which manages responsive loads, distributed resources and energy storage in local portions of the power grid. As previously mentioned, The characteristics of the controller are to meet the customers' expectations, preferences and system constraints while still ensuring a predefined level of reliability and power quality. It was shown that this is achieved through various information interfaces, collection of data and processing, and logical decision making.

Another proposed solution was the Energy Internet. This solution allowed for energy to be virtually stored, at least partially, instead of using conventional solutions of energy storage. This then lead to a reduction in demand (due to the electricity usage being scheduled in advance) and a possible increase in grid stability (as loads are not unpredictably connected to the grid). This was however based on the following key assumptions being true in such a system: Information is intelligently managed and shared, uncertainty must be managed through price elasticity (with a clearly defined model), smart meters must be present in the grid and be equipped with communication capabilities and have a unique address, the system must have the capability to forecast electricity consumption, and have multi-resolution agents (which cooperated with one another) that act on behalf of customers, the grid, and other parties.

Finally, Chapter 3 to Chapter 5 will present a Smart grid solution which is able to accommodate distributed resources and energy storage devices but also ensures that such technologies are effortlessly integrated, properly interfaced and suitably managed. Furthermore, the Smart grid described in Chapter 3 to Chapter 5 (referred to as the 'T'-Smart grid) will present a physical platform, which is based on key ideas and concepts of the Local Controller and Energy Internet solution, to create a Smart grid platform for such and other future technologies.

CHAPTER 3: THE 'T'-SMART GRID

3.1 OVERVIEW

This chapter presents a novel Smart grid solution comprising of two main components, namely a Control-component and a 'T'-component. A high level description will be given of this proposed Smart grid, its components and how these components will ensure the complete protection of distributed resources and also have the ability to reduce peak loading. (More details about this will be given in the chapters to follow.)

A brief overview of the control functions associated with the Control-component and the 'T'-component will also be discussed and it will also be shown how it integrates with Grid-components (sources, loads and energy storage elements) to realise a 'T'-Smart grid.

3.2 INTRODUCTION

Classical architecture of grids includes Generation-, Transmission-, and Distribution-stations. With the increase in global warming and the increase in energy costs, it is expected that renewable energy sources will be used more predominantly. To reduce energy losses and infrastructure expansion costs due to increased demand, these renewable energy sources should be located close to load centres, eliminating the need for long Transmission feeders and stations.

In the author's opinion; as urban areas are more developed, less space will remain for both the construction of generation- and distribution- stations. Generation stations may still however be allowed to take up some space, such as in the case of a wind farm, however it is believed that this will become less prevalent in future. Also, it is believed that distribution stations will not be allowed to take up any land space (above ground level) in future, and will be located in ground floors of buildings or preferably be small enough to take up no more space than the width of a cable trench and the length of current standard equipment (Mini-substations / Ring Main Units) installed on pavements.

Further, it is assumed that underground cable feeders be utilised instead of lines, despite the increased cost of material and labour, as cables are safer (because it is hidden from the public), not influenced by the surrounding environmental elements, aesthetically pleasing, takes up less space and will not be directly affected by lighting. (In the far future, this can even be extended to Gas Insulated Feeders which may become more prevalent as well.) However, in modern cities there is only space next to roads for a limited number of energy (electrical and gas)-, telecommunication-, water- services. As cities develop, residential buildings with low services infrastructure usage are replaced with high-rise buildings with significant higher usage of services. However, the space and routes available to deliver these services from the source to the customer remains unchanged and often very congested service areas lead to delivery constraints.

Thus, the author assumes that the solution to this would be that each load has its own energy source close to it. Then, the future Smart grid will only be a 'back-up' or secondary supply. Thus, if all loads have their own energy sources, no grid would be required.

However, while energy storage mediums are still being developed, and renewable energy source technology is still being adapted and researched to achieve this, some grid has to facilitate energy transfer in the interim as well as the end-state of this assumed grid.

This interim to end-state Smart grid must have the following attributes:

- ✓ Reduced peak demand to ensure reduced infrastructure expansion costs and the re-use of existing infrastructure,
- ✓ Enable the use of distributed renewable sources anywhere in the grid (Independent of where and how it is used in the grid),
- ✓ Enabling ordinary customers to buy, sell and store electricity anywhere in the grid, and thus possibly reduce the need for infrastructure upgrades and the impact on the environment.

As can be seen above, these attributes lead to a Smart grid which is more economical to install and maintain due to its reduced infrastructure needs. It will be shown that the 'T'-Smart grid achieves these attributes as discussed in this chapter and those to follow.

3.3 'T'-SMART GRID-COMPONENTS

The proposed 'T'-Smart grid is made up of several components as in a normal grid; however two intelligent components can be used to identify this unique Smart grid:

- ✓ Control - component (Similar to the current SCADA system, only more automated)
- ✓ 'T' - components

As seen in figure 3.1, the Control-Component has the highest level of authority and control, but as will be seen later, is not in absolute control of the day-to-day operations of the grid. All those operational functions are performed by the 'T'-components and it also has the ability to interact with normal Grid-components (sources, loads and energy storage elements), energy management devices, and existing grid infrastructure.

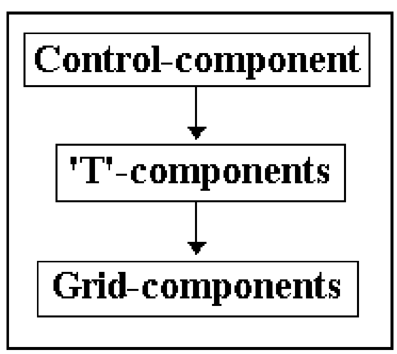

Fig 3.1: Control hierarchy of the 'T'-Smart grid

Consider figure 3.2 which shows typical 'T'-Smart grid. The Control-component is invisible as it is only responsible for background tasks and emergency switching functions as discussed later. The 'T'-component however is a three-port component which physically connects Grid-components such as energy sources, loads and energy storage elements together and acts as a local controller.

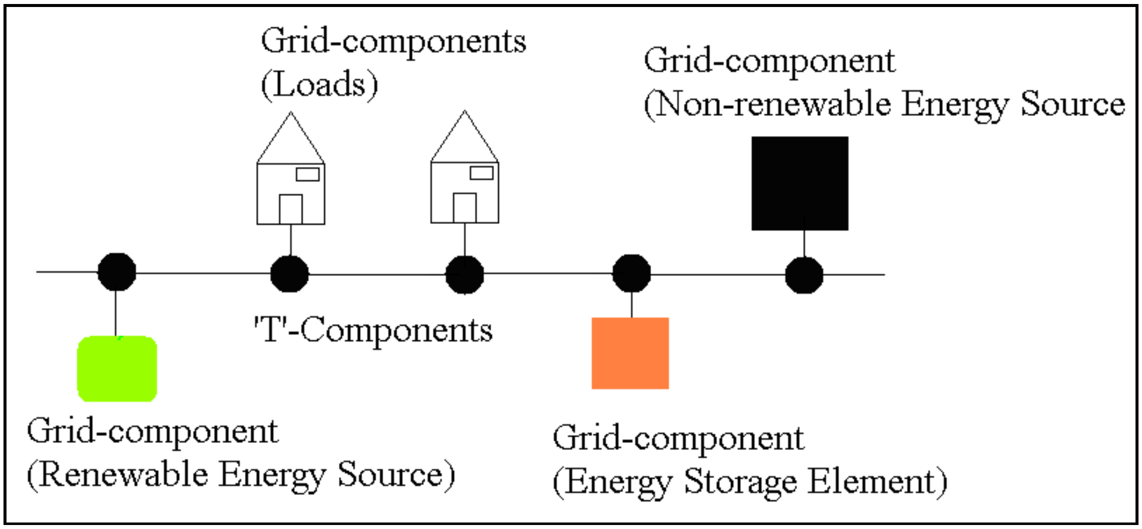

Fig 3.2: Typical ‘T’-Smart grid showing ‘T’-components and Grid-components

3.3.1 ‘T’-COMPONENT

Figure 3.3 shows a more detailed picture of the ‘T’-component with its three-ports that connects to grids, sub-grids and Grid-components. (Its internal mechanisms and control procedures will be discussed in more detail, in Chapter 4.)

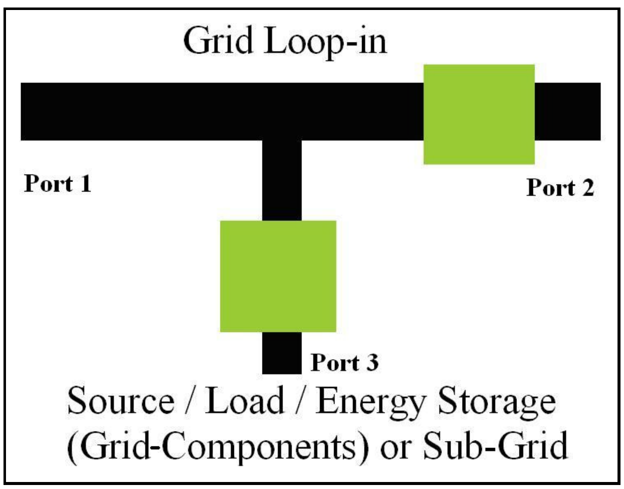

Fig 3.3: ‘T’-component with three input/output ports

The purpose of the ‘T’-component would be to always ensure supply of energy to loads. It will have three electrical connection ports which two of them will be considered as the ‘grid’ connection ports, and the third connection port will be used for sources, loads, energy storage elements and sub-grid connections. Note that the third connection port can either be a source (input) or a load (output), depending on the device or sub-grid connected to it.

For example, a residential customer might either be viewed from the grid’s perspective as a load or a source; because of the fact that distributed (and preferably renewable energy) sources might become more prevalent in future and integrated into a consumer’s household network.

Thus, for one instance in time, the consumer might require supply and the 'T'-component would ensure this energy flow occurs from the main-grid to the consumer. However, should the customer want to supply electricity back to the grid, then the 'T'-component would acknowledge this and supply this generated electricity to other parts of the nearby network, in a seamless fashion without interruptions to any of the consumers connected to the grid.

Also, as demand increases some consumer networks which were previously a load will deliberately become a source by selling surplus electrical energy that was stored up previously. This will be done to not only reduce peak loading but also to enable customers to gain financially through a smart metering system.

The 'T'-component's function can be divided into a main-function and sub-function to enable it to manage energy between other 'T'-components and Grid-components and sub-grids connected to it.

The main-function of the 'T'-component will be to 'combine' different sources to supply a load or 'split' supply for numerous loads, and accordingly communicate network loading to customers. (This network configuration and combining and splitting of sources will affect the energy charges for electricity and will be translated into network charges for the customers through a smart metering system.) The sub-function of the 'T'-component is to determine whether the device connected on the third port of the 'T'-component is a source, load, energy storage element or sub-grid and to manage it intelligently. This will be expanded on later.

Thus, the main-function of the 'T'-component will be to act on its own and make the necessary decisions to ensure an optimal configuration of the network by obeying an internal set of predetermined rules. These rules can be altered remotely or overruled by the Control-component, but in general this should not be required.

Another important feature of the main-function of the 'T'-component is the ability to restrict fault currents from propagating through the network. The protection method described in Chapter 4, will show that a fully distributed generation grid can be achieved without the need of considering the fault levels of the network. This is due to the physical internal design of the 'T'-component which limits fault current amplitudes and its integrated communication and protection system that can isolate faulty sections of the network instantaneously.

In effect, the 'T'-component will replace the 'Transmission Stations' and 'Distribution Stations' used in conventional grids.

The 'T'-component also has a sub-function (mentioned earlier) which acts as a control interface between the 'T'-components' main-function and those Grid-components, sub-grids or devices used by the customer, connected to it. Such devices may include energy management systems but this sub-function can also be tasked to manage the customer's electricity consumption requirements, as per the customers' preference, in the absence of such a system. Thus, the sub-function will also determine whether the 'T'-component should act as a load or a source, to the external network, depending on whether the customer is supplying energy or consuming energy.

This sub-function will then also be responsible for recording such energy flows and subsequently calculating the associated network charges. The actual electricity charges will fluctuate with network demand and how the network is re-configured to meet any specific demand, considering available sources.

The sub-function will also be responsible for the management of the distributed resources and energy storage elements of the customers. This is to ensure that the customer pays minimal costs for electricity by first using all the available energy from the local sources to supply the local loads and then to store the remainder the energy in local energy storage mediums. Only once all the local storage mediums are saturated, and there is extra energy available from the local sources after all the local loads have been supplied, will the extra energy be sold to the grid. This then leads to an overall grid which requires the bare minimum network as it only then needs to transport the shortfall in energy.

The main-function of the 'T'-component will thus communicate the network loading to the sub-function, and the sub-function will communicate back information about the customer's devices (sources, loads, energy storage elements or sub-grid) which will allow both functions to act intelligently and in the interest of both the grid and the customer.

3.3.2 CONTROL (SCADA)-COMPONENT

The Control-component will be in most ways similar to current SCADA systems. It will be able to monitor system conditions, take measurements of generated / consumed electricity and perform control functions under emergency conditions, or where absolutely necessary. Different to current SCADA systems, the Control-component will not have to be continuously operated (manned) and maintained to ensure supply and network stability.

Instead, the 'T'-component will interface with the Grid-components and sub-grids, and based on a predefined set of rules take the necessary action. Information about the Grid-components and the grid status will then just be relayed to the Control-component. The Control-component can then continuously monitor the grid (from this information) and perform off-line tasks which include:

- ✓ Determining a more optimised configuration for the grid (based on loading, voltage, power-factor, etc.),
- ✓ Emergency switching procedures (to be performed during malicious attacks),
- ✓ Identifying sections of the network which require strengthening (based on forecasted loading),
- ✓ Determining and identifying preventative maintenance on equipment (based on the age of the equipment, conductors and structures, if applicable, or due to repeated and unplanned overloading which reduced the network element's lifespan),
- ✓ Determining and monitoring the controlled temporary overloading of feeders,
- ✓ General monitoring of the grid and hence isolating of 'T'-components, existing (legacy) Grid-components or even sections of a grid where components are malfunctioning or not performing their tasks as per the 'T'-component's predefined set of rules.

  Depending on how the Smart grid was initially configured, other 'T'-components can also perform this function, if the 'T'-component's rules stipulate this isolation (and it is physically possible) or alternatively the Control-component can take over control at any given time.

Malfunctioning of 'T'-components may include failure to clear a fault, or simply not isolating a feeder on a grid that is overloading uncontrollably, etc. Hence the malfunctions here are more directed to the failure of internal components of the 'T'-component which prevents it from executing pre-programmed actions.

The entire 'T'-component, or only a specific port, can also be shut down remotely by the Control-component in cases of emergency, maintenance, stability reasons and disconnecting of customer connections due to overdue accounts.

- ✓ Facilitating real time information updates (which includes energy statistics of the grid and energy generation / storage / usage of individual connections), through the internet (or other means) to the customers. It is thus also responsible for converting measured values, as communicated by the 'T'-component, into bills for customers as well.

Thus, these are just a few of many off-line functions that will be performed automatically and the main aim of these functions is to improve the grid such that supply constraints do not reoccur in future (including emergency conditions).

One should notice the contrast of the current SCADA system and its grid architecture in relation to what is proposed for the future Control-component. In the current grid architecture, a SCADA system manages all distribution elements/components. This is equivalent to a Managing Director of a large company trying to give instructions to all its employees. This is impractical and poor management and control. (Hence, the 'T'-components controls the grid at a lower control level.) However, similar to a conventional SCADA system, the Control-component retains the ability to have the highest authority of control and to perform emergency, off-line, and other functions as needed.

Thus one can always think of the Control-component as the supervising management structure which can act at any time if required, while the 'T'-component is acting as a local controller which manages the grid and the Grid-components based on a basic set of predefined rules.

3.3.3 HIGH LEVEL CONTROL OF THE 'T'-SMART GRID

The fundamental first logic that is applied by the 'T'-component to control the network, is based on a system of priorities. All Grid-components are assigned priority values, which are determined by the Grid-operators (grid owners). For example, Grid-operators may choose renewable sources to have high source priority values and industrial customers to have high load priority values. Then, the 'T'-component will use the renewable energy first to supply industrial customers and only after these sources have been depleted, move over to non-renewable sources. Should energy remain after this, only then would commercial customers and residential customers be considered based on the priority values assigned to them by the Grid-operators.

Energy storage elements can act as loads or sources, depending on whether they are charging or discharging energy. They can also be assigned source priority and load priority values which can lead to very advance management techniques. (Sub-grids are controlled in a similar way.)

This will be described in more depth in the chapters to come, and it will also be seen that regional demand in a network, or constrained feeders, can influence this control method such that a more intelligent outcome is reached where more loads are supplied and less is then shed.

Note as always, the Control-component can still override this function if needed.

3.4 CONCLUSION

This chapter gave a brief high level explanation of a novel Smart grid solution together with its key components. (This will be expanded on in the chapters to follow.) It is assumed that the grid of the future would mainly consist of islanded loads and sources connected together by small grids, while the main-grid will only be used as a back-up supply. (Hence, if loads have nearby sources, a main-grid may not be required.)

Until such energy storage and compact energy generation technologies are developed to realise this, an interim to end-state grid with its components would be required. The Smart grid presented aims to meet this criteria and consists of mainly two components: a Control-component and a 'T'-component.

The 'T'-component has three connection ports of which two interfaces with the main-grid, and the third port (which can be an input or output) interfaces with a source, load, energy storage element (Grid-components) or sub-grids. The 'T'-component will change its operation depending on: whether energy is used or supplied by the customer's devices, general grid conditions, a set of pre-defined 'T'-component control rules, and customer preferences.

Changes that can affect grid conditions include: grid demand; connection ports changing from sources to loads or vice versa; certain sources / loads / energy storage elements being connected / disconnected due to faults; sub-grid network-, source-, loading-, storage-changes; general network limitations; etc.

The 'T'-component has a main-function that interfaces with other 'T'-components and the network while the sub-function interfaces with Grid-components (and customer devices) and sub-grids.

The main-function of the 'T'-component cannot only combine inputs from different sources to supply a load, or split sources to supply different loads (i.e. changing of network configuration), but also ensures that the fault current through it is restricted. In addition, it has the ability to make use of its own communication and protection system between other 'T'-components to isolate a faulty section of the network. (To be expanded on in the chapters to follow.) This then greatly assists the integration of distributed sources.

The 'T'-component's sub-function will facilitate and manage the interaction of distributed sources, loads, energy storage elements and sub-grids of customers (and the electricity consumed/supplied by customers), with the main-grid. This management interface will also be a key enabler to reduce the system peak as will be seen in the next chapter.

The Control-component however, only monitors and collects data from the 'T'-components and performs several off-line functions. Some of these functions include: re-configuration of the grid (for optimal energy use), emergency switching, identifying upgrades (based on load forecasts), determining equipment to be maintained (based on age and previous overloading), controlling and monitoring feeder overloading, electrical isolating functions (on faulty equipment) and the transmission of real-time grid and customer information.

The grid is managed mainly by the 'T'-components which supply loads from sources, based on a priority system whereby the priority values are defined by the Grid-operators (grid owners). Hence, the highest priority source supplies the highest priority load first. (Energy storage elements are controlled in a similar fashion, depending on whether energy is stored or released.) However, in the chapters to follow it will be shown that in some cases, the 'T'-component deviates from this rule to achieve a more optimum energy solution.

The Control-component together with the 'T'-component is the fundamental basis of the novel 'T'-Smart grid presented in this dissertation.

CHAPTER 4: 'T'-COMPONENT DETAILS

4.1 INTRODUCTION

In the previous chapter, a 'T'-component was briefly described which forms part of the 'T'-Smart grid. This chapter aims to further explain in detail the following about the 'T"-component:

- ✓ Its basic operation (with an example) taking into consideration network configuration and available energy sources,
- ✓ 'T'-component properties (essential and non-essential),
- ✓ 'T'-component connection ports and purpose of each port,
- ✓ Fault current amplitude limiting and negating the propagation of fault currents,
- ✓ Ensuring complete protection between Grid-components,
- ✓ Proposed physical internal layout,
- ✓ 'T'-component's limitations and subsequent effects of these limitations,
- ✓ Isolating faulty networks and closing of N/O (Normally Open) points automatically,
- ✓ Creating a discrete 'T'-Smart grid to allow optimal decisions and energy transfer,
- ✓ 'T'-component process control based on priority values assigned to Grid-components,
- ✓ 'T'-component interaction with main-grids, sub-grids and sub-sub-grids,
- ✓ Calculation of demand and compensating for constrained networks, varying network usage (in time and distance), and varying grid conditions,
- ✓ Intelligent interaction with energy storage elements which can function in three different modes of operation,
- ✓ The 'T'-component's control process to manage itself and the entire grid,
- ✓ Its mathematical stability,
- ✓ Customer billing and accounts.

The 'T'-Smart grid only comprises of Grid-components (sources, loads and energy storage elements), feeders (conductive mediums), a Control-component and the 'T'-components which must ensure seamless integration of all Grid-components and the protection of the entire grid.

4.2 EXAMPLE

A brief high-level example is presented to show the typical interaction between 'T'-components and the grid shown in figure 4.1.

The thin black lines represent conductive mediums, the black circles 'T'-components, the green blocks: renewable sources, and the black blocks: non-renewable sources. The bigger the block, the more generation capacity the source may have at a given point in time.

In figure 4.1, one will notice non-renewable and renewable energy sources all connected in a ring formation. This is not a requirement of the 'T'-Smart grid and only a possibility of many different configurations.

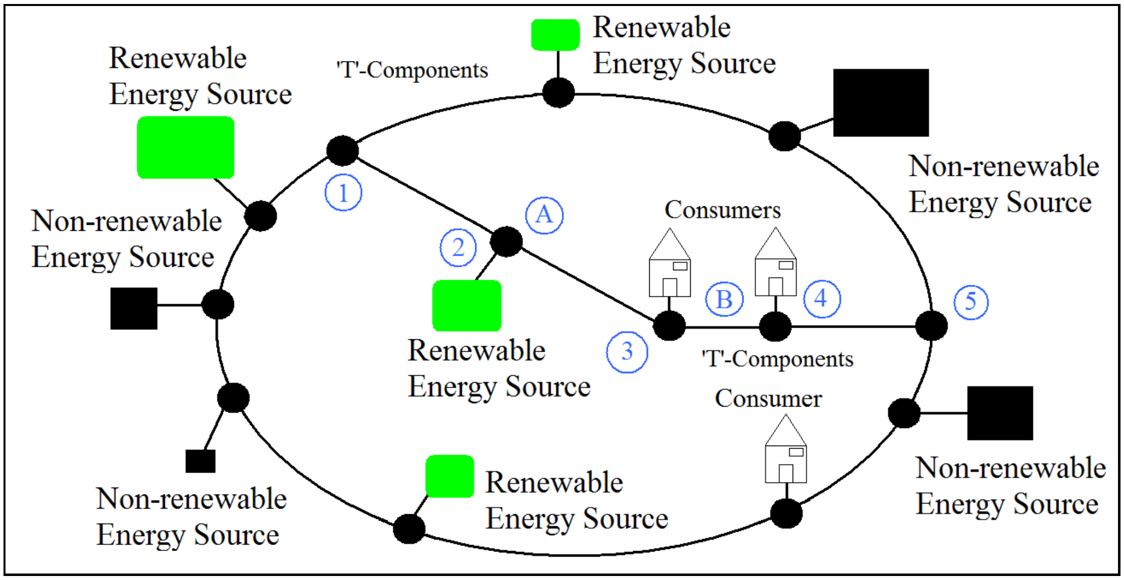

Fig 4.1: Example grid layout with distributed sources, loads and 'T'-components

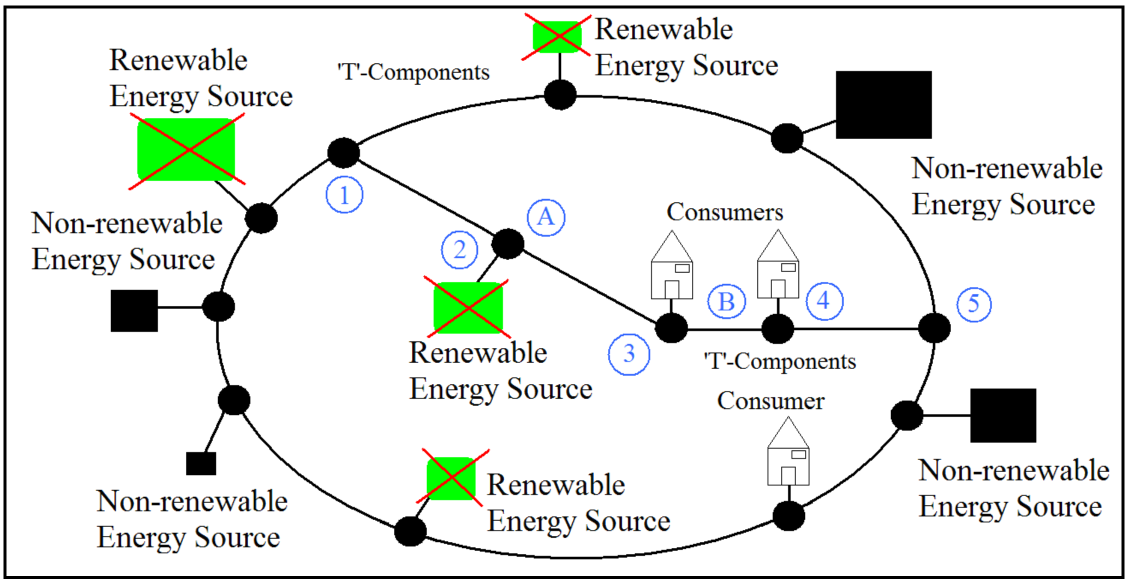

Fig 4.2: Example grid layout - All Renewable sources cannot generate electrical energy

Consider figure 4.2 and assume all renewable energy sources are unable to generate any energy in a given period of the grid. The consumers (loads) at 'B' in the figure will then have to rely on 'T'-component 5 for supply, assuming:

- ✓ 'T'-component 1 is further away than 'T'-component 5,
- ✓ The energy supply priority of the non-renewable sources connected to 'T'-component 5 is higher than those connected to 'T'-component 1 and,
- ✓ The two non-renewable energy sources on the right of figure 4.2 have sufficient energy to supply all the loads at 'T'-component 3 and 4.

Thus, 'T'-components 3 and 4 will still sense the availability of supply from two different directions because it is a ring connected network. They can then use portions of energy from each direction to supply all the consumers which may be residential, commercial or industrial. (The energy is added together based on a pro-rata formula. This will be discussed in more detail later.)

However, from the perspective of 'T'-component 4, 'T'-component 5 is closer, it conducts energy with a higher supply priority (when compared to the energy from 'T'-component 1), and it has sufficient energy available to supply the load connected to it. 'T'-component 4 will then distribute the energy to the first customer as well as to 'T'-component 3 which will in turn supply the second customer.

'T'-component 3 will then attempt to secure a back-up supply through the supply direction of 'T'-component 2 and 'T'-component 1, in case the supply from 'T'-component 5 fails. (It will thus not be used until 'T'-component 5 or a feeder to it fails.)

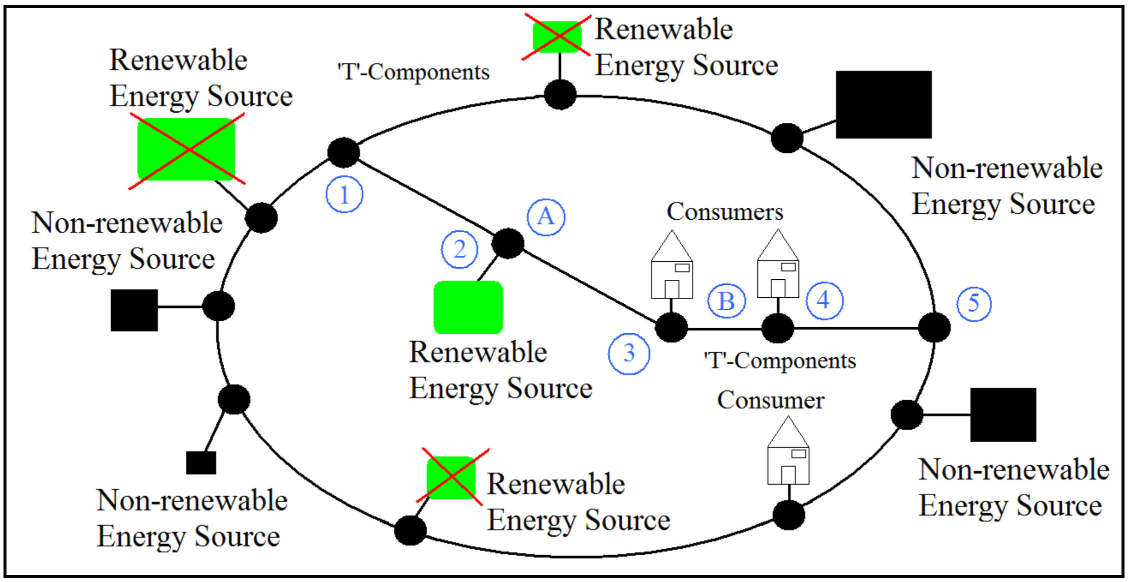

Fig 4.3: Example grid layout - All Renewable sources, except source 'A', cannot generate electrical energy

Consider now figure 4.3, and assume that the renewable energy source at 'A' in figure 4.3 regains generation capacity for a given time in the grid. 'T'-component 2 will sense this and relay the energy to 'T'-component 3. (It will not be necessary to relay power to 'T'-component 1 as there are no loads in that network and supply to the loads at 'B' through 'T'-component 5 will be at a significant increase in network length when compared to the supply through 'T'-component 3.)

Assume the Grid-operators assigned renewable sources a higher priority than non-renewable sources. Then, 'T'-component 3 will notice that the source at 'A' is a higher priority energy source and use a portion of this energy to supply the customer connected to 'T'-component 3. This does not happen instantaneously as the energy needs to be transported through an FCL, as discussed later.

Then after the customer at 'T'-component 3 has received all its requested energy (assume there is sufficient supply available), the renewable energy will propagate further to 'T'-components 4. Assume that the energy remaining after the load supplied at 'T'-component 3 is insufficient to supply the load at 'T'-component 4, then the highest possible portion of renewable energy will be combined with the non-renewable energy source (from 'T'-

component 5), to supply the load. (The only reason why the renewable source is preferred over the non-renewable source in this example is the fact that it was assumed that the Grid-operators assigned the renewable sources higher priority values.)

Similarly, if the renewable energy source's available energy starts to decay, then this will be sensed automatically by the 'T'-components so that a higher portion of energy can be obtained from other lower priority sources (non-renewable energy in this example) as the renewable energy's supply is phased out.

Note that the renewable energy sources at 'T'-component 1 (figure 4.3) may also start generating electrical energy in future. It may have a higher or lower priority when compared to the source at 'A' in the figure. The 'T'-components will communicate with each other, so that the best possible, most reliable and highest priority energy are supplied to the consumers in a controlled fashion or based on the way the Grid-operators have set up their control rules and network layout.

As stated previously, renewable energy sources were considered higher priority energy sources than a non-renewable energy sources in this example. However, this decision is determined by the Grid-operators during the setup and management of the 'T'-Smart grid and factors such as generation cost, impact on the environment, supply capacity, etc. may determine the actual final priority value as discussed later.

More complex examples will be given in Chapter 5, to further explain the operation of the 'T'-component Smart grid in more detail.

4.3 'T'-COMPONENT PROPERTIES

In order for the 'T-Smart grid to realise its full potential, the 'T'-component must have the following properties:

- ✓ The ability to seamlessly integrate and manage an unlimited number of Grid-components (sources, loads and energy storage elements) in the main-grid and sub-grids such that network capacity constraints and peak loading will be minimized.

- ✓ It must ensure complete electrical protection between all Grid-components and sub-grids by eliminating the propagation of fault currents and limiting fault current amplitudes (to reduce associated infrastructure fault capacity upgrades and earthing requirements).

- ✓ The ability to be fully controlled remotely by the Control-component. Functions may even include disconnection a specific port for maintenance, which is automatically followed by an isolating and earthing function by the component. (This automatic isolating and earthing functions are performed by any and all ports when needed.) The 'T'-component should still be able to function in accordance with the predefined rules, but only considering a reduce number of ports.

- ✓ In case a fault is detected, external from the 'T'-component, then that port (and conductive medium) must be automatically disconnected, isolated and earthed. It can also alert the 'T'-component on the other side to do the same, in-case the other side only had loads connected to it, and was unaware of the up-steam fault. It can then alert maintenance crews of the problem, and even give an indication of the fault type (based on fault analysis) and where (based on impedance type protection) the fault may be.

- ✓ Communicate important grid parameters to the customer (or customer interface) which will indicate in real time the grid's total available energy, the total connected load, network capacity constraints, the grid's demand (and whether it is caused by energy deficiency or grid limitation(s)), and the priority of the Grid-components connected to the different 'T'-components in a sub-grid or lumped value for a number of sources, loads, or energy storage elements connected together.

- ✓ Report back to the Control-component energy flow values measured throughout the grid as well as the grid's and the sub-grid's electrical configuration.

- ✓ Physically, have the functionality to convert (from the available energy that is flowing through it) a suitable control voltage (and supply) to be used to drive the electronic hardware inside the 'T'-component. This consumed energy is also to be metered and reported to the Control-component. This supply should also have its own independent energy storage device, enabling the electronic hardware to remain responsive even if it did not function for an extended period of time (or disconnected from the grid). Should this energy storage device ever run out of energy, then the 'T'-component will shut down in a predetermined manner, such that when energy to it is restored, it will perform the basic tasks to start-up and operate correctly, before starting any switching (in the grid), in the shortest possible time.

The following properties are not essential to the success of the 'T'-Smart grid but would advance the future applications of this system:

- ✓ The ability to interface and accept any signal input from any Grid-component or sub-grids and then to convert these electrical signals to the grid's standard voltage(s) and frequencies (if more than one).

  This will allow smaller sources (at lower voltages) to combine their energy and supply larger loads (at higher voltages) under emergency / contingency conditions.

  Some signal variations may include:

  - In-phase (with the grid) AC signals
  - Out-of-phase (with the grid) AC signals
  - Single-phase AC Signals
  - Double-phase AC signals
  - Three-phase AC signals
  - (Varying / Constant) DC signals
  - Voltage step-up / step-down signals

  This property must also include power factor correction and compensation for harmonics and all other signal related correcting functions.

  The grid's voltage and frequency can be chosen based on efficiency, space, environmental aspects, etc. and can be different between its three ports.

- ✓ Perform self-diagnostics tests, continuously, and disconnect from the grid if an internal malfunction is detected.

  Once it sensed an internal fault had occurred and disconnected itself from the grid, it should also alert the Control-component of this (with a full diagnostics report) and also alert maintenance crews of its location and fault type.

  It can also do the same for minor maintenance or planned maintenance (as determined by the Control-component) and only switch-out at a pre-defined and communicated time, such that it would have minimum impact on the grid.

  Note that as mentioned, the 'T'-component will alert maintenance crews when it requires repairs, and failing this, the Control-component will take over and perform the necessary alerts and tasks.

- ✓ The 'T'-component must be designed such that it can be fitted into a socket, such that it can easily be replaced by another within minutes, in case of unmaintainable or catastrophic failure. The broken / malfunctioning component will then be brought to a facility where it will be repaired. (Faults / errors on the component will also be investigated and analysed so that it would not be repeated in future designs and internal component configurations.)

- ✓ A predefined and industry accepted standard protocol used between the Control-component, 'T'-components, Grid-components and Customer interface units which is developed as part of the Smart Home concept. (Due to the nature of the Smart grid, and the communication interface and speed that it requires to function correctly and efficiently, it is assumed that fibre optic communication or signals imbedded in the supply voltage signal would be the optimal solution.)

- ✓ Have the ability to sense temperature, current flow, stress on insulations, etc. of conductive mediums (feeders) and determine its maximum continuous, emergency or cyclic loading capacity. (Ambient temperature must also be taken into consideration when this is determined. i.e. Feeders may be able to carry more load in winter.) Then, this sensed and calculated maximum capacity of a specific feeder must be updated in real-time, to the 'T'-components and Grid-components.

  This same property should also detect and report the location of hot-spots, installation / mechanical problems and other abnormalities on feeders. (If preventative maintenance is required, then this alarm should be relayed to the Control-component as well.) This property can also be extended further, to indicate only sections of the feeder which might be under critical stress. Then the energy through the compromised element can be reduced or cut-off, depending on the severity of the problem.

- ✓ Have a built-in prediction system (e.g. Finite Impulse Response- / Infinite Impulse Response- / Kalman- / Wiener- adaptive filters / Neural networks / other prediction methods or combination thereof) which will study three main aspects. It will first study and predict On / Off-peak times of the grid (or sub-grid), and secondly study and predict the loading habits (time of use and energy quantity) of the users. Then thirdly, it will study and predict the time and quantity of when energy is generated by locally connected sources. (This information must be recorded on an hourly, daily, weekly, monthly and yearly basis to form a comprehensive database for forecasting.)

Based on this information, the 'T'-component's sub-function can ensure that the energy storage device is controlled in such a manner that charging and discharging occurs at an optimal time to ensure minimal or no impact to the grid and its resources, and also allows for the smallest energy storage element to have the maximum beneficial impact. (This is because the load requirement and source availability will be known, hence the energy shortfall and required energy to be stored can be calculated and planned, for every given point in time of the grid.) This same information can also be displayed through a customer interface to assist the user in reducing or moving his / her loading when the grid is experiencing peak demand.

It should be noted that for a sub-network with different sources, loads and energy storage elements all functioning at different priorities, and where the probability exist that some loads may be shed by customer preference rather than to supply it, the basic principle of it remains the same. It is only how these forecasts of the different grid elements are integrated together, based on customer preference, which will make the difference and have to be taken into account.

- ✓ Using the previous mentioned function communicate to the customer (or through the customer's interface), advise on the size of the local source or energy storage element required to reduce electricity charges (in general, or for On / Off-peak times) and ultimately achieve the maximum profit from the grid (by selling electricity to it) for the given network constraints, loads, sources and energy storage elements (from other customers) in the vicinity of the customer.

  Also, customers can be motivated to move load to different periods by not charging a peak tariff alone, but also rewarding those customers who have a flatter loading profile (or higher degree of utilisation) with smaller peaks stretch-out over longer periods of time. (This can be the main trigger for installation of energy storage devices which could later result in the installation of local generation capacity, and ultimately negate the need for the grid as the primary source and distributer of energy.)

- ✓ The ability to manage the customer's loads directly (or through a customer interface) based on the customer's preference. For example, washing machines are a common example of a load that can be moved to a different time of electricity usage, with minimal impact on the customer. Based on the customer's settings, this load can either be moved to an off-peak time (which is generally accepted to be off-peak such as after midnight) or the 'T'-component can intelligently advise, based on information from the forecast function, when the grid is in off-peak mode and then connect the load to the grid in that time. (It is believed that the second function will become more beneficial as grid users may start using any of the Smart grid system solutions in future which can lead to On / Off-peak times becoming very difficult to predict [4].)

4.4 'T'-COMPONENT OVERVIEW

In short, the 'T'-component is a three port power transfer device which allows energy inputs / outputs on three ports, where two ports are connected to the grid, and the other port is connected to sources, loads, energy storage elements or sub-grids (all possibly belonging to a customer). This symbol for the 'T'-component is depicted in figure 4.4.

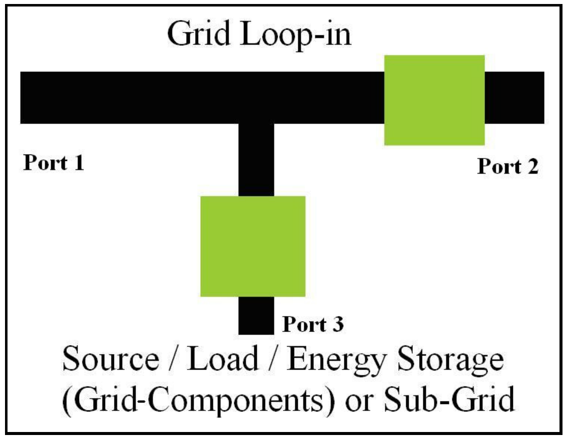

Fig 4.4: 'T'-component with three input/output ports

The green blocks inside the 'T'-component of figure 4.4 represents a Fault Current Limiter (FCL) described later.

The 'T'-component strictly follows a fixed set of rules to manage the grid's components (which includes sources, loads, energy storage elements and sub-grids) and also communicate priority and demand measurements (explained later) to customer devices which include normal meters, Smart home devices or even additional energy management devices. All rules are pre-defined and pre-set by the grid operator which then allows the grid to operate in a predictable and commercial fair manner without human interaction.

It is envisaged that this form of automated infrastructure in a grid will replace conventional transmission-, distribution- and switching- stations. It should also be mentioned that the 'T'-component will determine the quantity and time when energy is allowed to be supplied, stored or consumed.

Port 1 and Port 2 are connected to the grid and can either be an input or output at any given time. If port 3 has a source connected to it and its supply needs to be divided into different parts of the network, then both Port 1 and Port 2 will be outputs as shown in figure 4.5.

Also, both ports can be inputs if it is necessary to combine energy from different sources to supply a given load at port 3 as seen in figure 4.6.

If the load or source connected to port 3 is relatively small, compared to the grid, then Port 1 will either be an input / output and Port 2 the opposite, depending on the direction of the energy flow.

So, the energy that entered can be added to the energy of the assumed source connected to port 3, and then again continue onto the next 'T'-component or, energy can enter the 'T'-

component which then supplies an assumed load on port 3 and continues to the next 'T'-component (assuming the grid energy is more than what is required by the load).

Assume the energy enters at port 1 and leave at port 2, and consider figure 4.7 which depicts these scenarios.

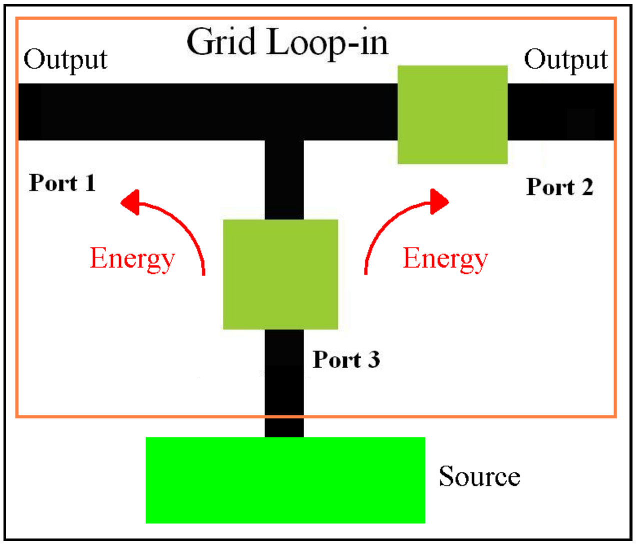

Fig 4.5: 'T'-component dividing energy from a source

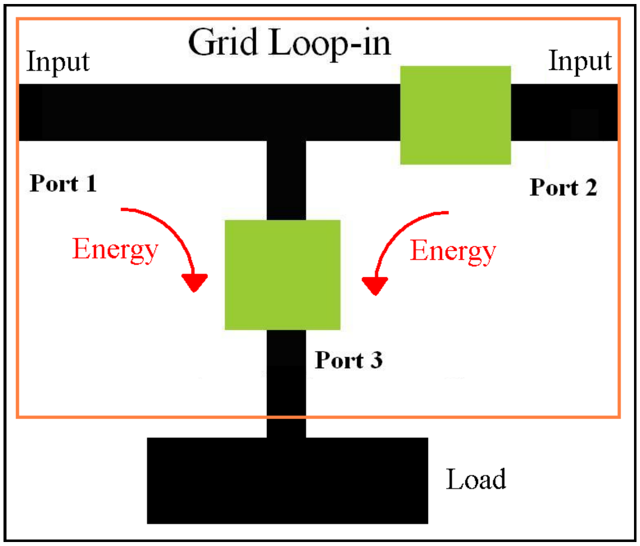

Fig 4.6: 'T'-component combing energy to supply a load

The ratio in which energy is split or combined by the 'T'-component is determined by external grid factors which are communicated to the component, under the priority section as explained later. Hence, the source or load's priority determines the quantity of energy to be added or subtracted while the Fault Current Limiter (explained next) is responsible for the physical implementation thereof.

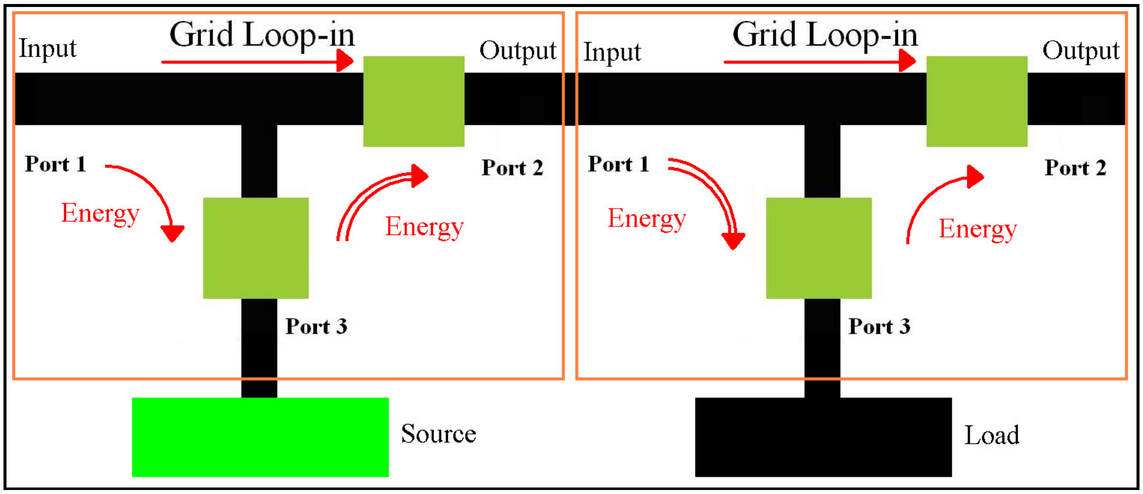

Fig 4.7: 'T'-component adding (left) and subtracting (right) energy

4.5 Fault Current Limiter (FCL): Ensuring protection between Grid-components

One of the most important physical properties of the 'T'-component is to ensure seamless integration between loads, sources and energy storage elements and to reduce the associated fault levels which impact on the grid. This is achieved through many interfaces and management systems but the core of the solution is a sub-component of the 'T'-component, referred to as the 'Fault Current Limiter' (FCL).

As the name suggests, this proposed mechanism limits fault current amplitudes and prevents fault current propagation, and in addition, allows for different voltage levels (AC or DC) to be used or recreated between Grid-components (for seamless source integration), as needed.

Consider Fig 4.8 which depicts the FCL component and functionality, which is an integral part of the 'T'-component.

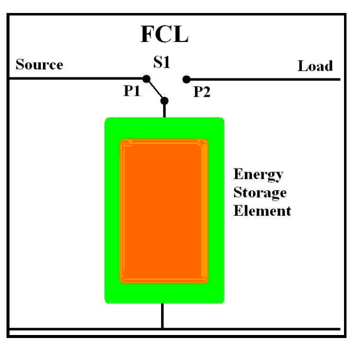

Fig 4.8: Fault Current Limiter (FCL)

The function of the FCL is to temporarily store energy from a source (or the grid / neighbouring 'T'-component) in a temporary energy storage element (indicated by the green block in Fig 4.8 and 4.9) when switch S1 is in position P1. Once fully charged, it discharges to a load (or the grid / neighbouring 'T'-component) when switch S1 is moved to P2. The cycle is repeated continuously.

By following this process of first storing the energy, and then discharging, before transporting it further into the grid, the fault current amplitude (under fault conditions) is limited to the energy capacity of the temporary storage element used. (If higher frequencies are used for the switching of S1, then the temporary energy storage element required can be smaller in terms of its energy storage capacity, which will result in even lower fault levels and possibly a cheaper device.)

This temporary energy storage element is the FCL and together with the switching mechanism described next, ensures fault current amplitudes are limited and different signal shapes are emulated to ensure compatibility with numerous source outputs.

The 'T'-component will have many FCLs as will be seen later. Assume for now a 'T'-component with only two FCLs and consider figure 4.9 which shown two FCLs connected in parallel.

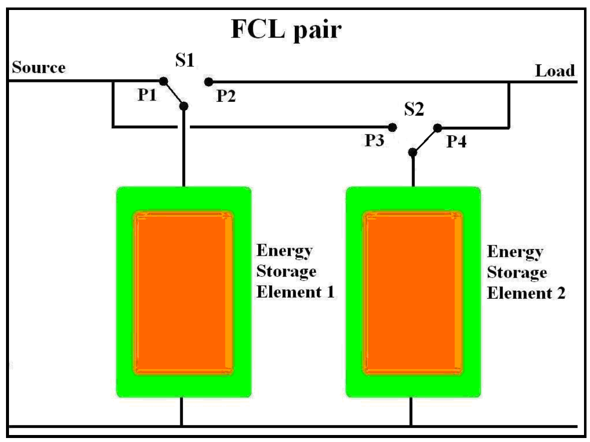

Fig 4.9: FCL pair with S1 and S2 operated out of phase

This setup allows one FCL to discharge its energy (gathered from a previous cycle) while the other charges. i.e. If S1 is connected to P1 then S2 is connected to P4. (The first temporary energy storage element is charging energy while the second temporary energy storage element is discharging its energy.)

Once the second temporary energy storage element has no more energy to supply, then S1 moves to P2 and S2 moves to P3. (The first temporary energy storage element is now discharging energy while the second temporary energy storage element is charging energy.)

Thus, the assumed 'T'-component will have two FCLs with a chop-over circuit so that the output energy signal created from the one FCL (and supplied to the grid / neighbouring T-component), is not the same FCL which is being charged at that moment (by the grid / another neighbouring T-component). This process will repeat itself continuously.

If a multiple FCLs are utilised in parallel, then signals of different amplitude, phase and frequency can be accepted and recreated by varying the frequency and duty cycle of the switches, which will then ultimately allow any electrical energy to be accepted and adapted / reshaped (if needed) to ensure seamless integration between Grid-components and energy signals.

Thus, any section of the grid between two 'T'-components or 'T'-components and Grid-components can be seen as a (limited) source connected to a conductive medium and a load.

One possible physical solution to this concept might be the use of a switch-mode power supply. For example, a switch-mode power supply which is part of a computer, receives an AC input voltage which is then rectified and filtered to obtain a DC voltage signal. Through the use of power electronic circuitry, this DC voltage signal is switched on and off at frequencies significantly higher than the input voltage signal's frequency (typically 10kHz to 1MHz) to produce a AC signal which is then passed through a high-frequency transformer and filtered to obtain a DC signal again. [11]

Hence, through the use of switch-mode power supply different voltage waveforms can be created. A higher switching frequency also enables the use of smaller, lighter, and a lot more economical components. [11]

Please note that the temporary energy storage elements / FCLs are not bulk energy storage elements. They should not be confused with externally connected bulk energy storage elements which are used to manage peak demand and address network capacity constraints.

This solution further assists with the integration of the conventional grid with the 'T'-Smart grid as it creates an isolated connection between the two grids.

In addition, the 'T'-component will be able to sense the rate at which the temporary energy storage element / FCL charges and discharges, and based on this determine whether a fault has occurred. If a fault has occurred it will disconnect from the grid which will prevent the fault current from propagating further. (Note that conventional protection methods / philosophies such as Impedance (distance)-, earth fault- and differential- protection may still be present in the 'T'-component as well.).

It should be noted that although a specific side of the FCL is referred to as the source side and the other the load side (in figure 4.8 and figure 4.9); the apparatus is completely bi-directional in nature.

Finally, reducing the fault current amplitude will reduce the cost associate with acquiring equipment with high fault ratings as well as earthing infrastructure (earth rods, earth mats, etc.) requirements which are not only expensive (in poor soil conditions) but is only fully utilised under fault conditions. Furthermore, it will increase public safety as touch and step potentials related to the fault current amplitude will be reduced.

4.5.1 PROPOSED 'T'-COMPONENT INTERNAL LAYOUT USING FCLS

The 'T'-component's proposed physical internal layout is depicted in figure 4.10.

Figure 4.10 shows the Grid-component port (port 3) and two grid connection ports (port 1 and port 2) at the top. Each port has a Voltage Transformer [VT] (or equivalent sensing devise) in order for the 'T'-component to sense and to ensure it re-creates (depending on whether the energy is flowing into or from the applicable port) the correct voltage signal amplitude, phase and frequency.

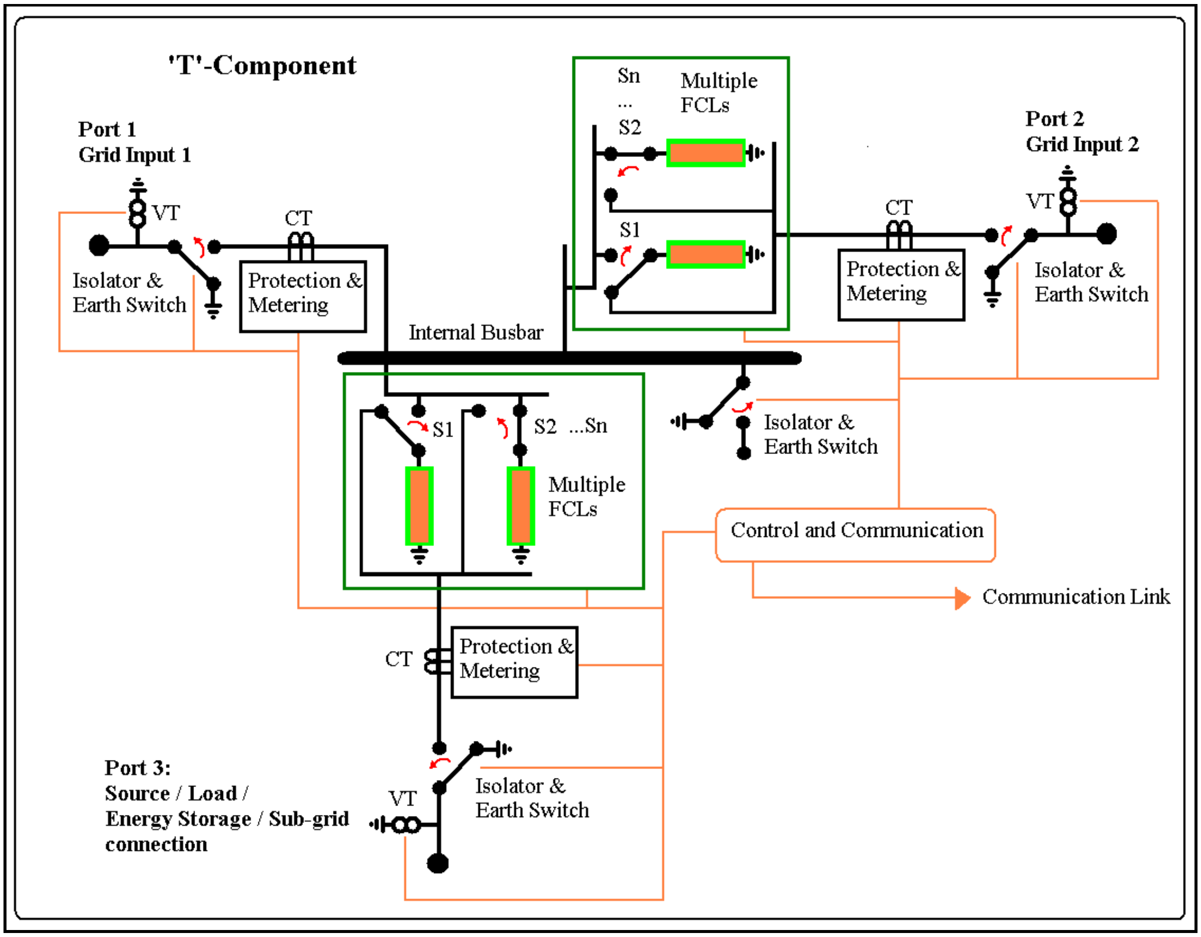

Fig 4.10: Internal layout of 'T'-component with multiple FCL sets

This is followed by a (motorised) isolation link, which is used to connect, disconnect and earth a feeder connected to a port of the 'T'-component. (This is the equivalent of a 'three-position' switch, commonly used in industry.) After this, a Current Transformer [CT] (or equivalent sensing devise) is used for various protection and metering applications.

The energy from or to a port is then fed to a system of FCLs (with switches (S1 to Sn) which accept or adapt voltage signals. (It is envisaged that this could be affordable semiconductor switches in future). This then all connects to a common busbar which also has an isolating and earthing facility.

Note that the earth-switches shown in figure 4.10, are used for maintenance purposes. Hence, the earth switches on the ports are used to earth the outgoing electrical feeders and the earth switch on the busbar is used to earth the 'T'-component internally.

The orange line in figure 4.10 depicts the communication link between the various internal components inside the 'T'-component and the internal control system labelled 'Control and Communication'.

The internal control system is a computer which executes all the functions of the 'T'-component and communicates with the Control-component and with other 'T'-components.

(Some of the information communicated includes the energy flow of the grid, grid configurations, abnormalities (faults), general and customer metering, etc.)

4.5.2 FCL ENERGY TRANSFER LIMIT AND GRID DEMAND

On closer inspection of figure 4.5 to figure 4.7, one would notice that the FCLs are only connected to the port 2 and port 3.

Thus, the FCL on port 2 (grid-connection port) not only limits the fault current from propagating in the grid, but has its own maximum capacity rating for the transfer of energy as well, which is matched to the capacity of the internal busbar and connected feeders. Hence, the normal energy transfer capacity of the FCL limits the amount of energy flowing into, out-of and through the 'T''-component.

Note that if a large load is connected to port 3 (Grid-component port) and requires energy from both port 1 and port 2, then the FCL of port 2 would allow energy to flow into the 'T'-component up to the FCL capacity. Also, energy will flow in at port 1, which is connected to port 2 of a neighbouring 'T''-component (consider figure 4.7) which also has an FCL and a maximum FCL capacity. If all port 2 FCLs, busbars and feeders are matched in terms of maximum capacity, then it means that in this case, port 3 will see the energy of 2 x FCL's capacity as energy from both sides are combined to supply the load. This results in the FCL capacity of port 3 to be twice the size of that on port 2. (Note that the busbar's rating is not exceeded as the energy flowing in from each side is still within its limit and that of the FCL.) Hence, the port 3 FCL will never allow energy more than twice the FCL limit (of port 2) through.

This is also true for the reverse scenario where a source is connected to port 3 and energy is split into two different directions.

Also, if a source is connected to port 3 and it has energy in the range of the FCL's capacity or higher, and an energy signal equal to FCL flows in from port 1 (and wants to exit on port 2), then that source will simply not be used, assuming it has a lower priority than that of the in-flow signal's priority. Otherwise, if it has a higher priority, then the 'T'-components would not have used energy from the other source in the first place, as it would know and would use this higher priority source first (connected to port 3). Thus, if energy is flowing in only one direction, it is limited to the FCL's capacity.

The previously mentioned limiting of energy will affect the demand calculation of the grid.

The previous explained scenarios can also be viewed as follows: If the difference between the total energy available in a grid and that of the total load to be supplied is greater than the FCL limit of port 2 (grid-connection port), then this will also result in a reduction of available energy (source) capacity or a reduced energy transfer (load) capacity due to the FCL's limit.

Because of the reduced capacity to supply energy or transfer energy, this impacts on the grid's demand (or sub-grid) because at a given time, the liming FCL (or feeder) can only let a given amount of energy through.

Note however that the 'T'-Smart grid is set up such that the network infrastructure (FCL / feeder / busbar limits) never plays a role in the demand calculation, until it becomes the limiting factor. If it does become the limiting factor, then the increase in demand due to the infrastructure limit can result in an increase in revenue collected which can later be used to upgrade this constrained element.

Thus, it also means that when a source is connected to a Grid-component port (port 3) and its signal amplitude is greater than the capacity of the FCL's limit, then the difference in energy would be lost. However, if a load is connected to a Grid-component port (port 3) and it exceeds that port's FCL limit, it has to be shed in total as one cannot partially supply a load. The only exception is energy storage elements which will charge (while emulating a load) and discharge (while emulating a source) any amount of energy within the port's (port 3) FCL limit while also taking into consideration the physical charge and discharge rates of the energy storage element.

4.5.3 FCL PROTECTION: ENABLING AUTOMATIC SWITCHING OF N/O POINTS

Future grids, as the 'T'-Smart grid will have to detect faults and take the necessary action to ensure grid stability and supply to all loads (if possible), automatically.

The 'T'-Smart grid, like current grids and future grids have a wide range of protection methods to safeguard the network against faults but currently, switching of N/O points in the network remains a manual task perform by Grid-operators.

In addition to limiting the fault current with an FCL in a 'T'-Smart grid and measuring the discharge rate from the FCL as means to sense a fault, a condition must be defined when a Normally Open (N/O) connection in the grid may be closed (connected) to obtain supply from another source if a fault occurred on the 'T'-Smart grid.

Different means could have been used to communicate a fault throughout the network. Note that due to the use of the FCL in the 'T'-Smart grid, the FCL would eliminate a fault between two 'T'-components and the rest of the network will not be aware that there is a network fault, unless it is communicated to the other 'T'-components.

Sending a signal to all the 'T'-components that a fault occurred not only takes up bandwidth, but also, if communication fails, then other 'T'-components will be unaware of the problem which could lead to network instability, priority and demand values being calculated incorrectly (discussed later), Grid-components being disconnected unnecessarily, and overall general malfunction.

Thus, to overcome this problem, the number of 'T'-components left and right of a given 'T'-component is known and programmed into the 'T'-component. Then, while the grid solves itself for the next grid state, it also counts the 'T'-components left and right of it and compares it to the original stored value. If the numbers do not match, then the N/O (on that 'T'-component only) towards another network is closed and the faulty feeder is isolated. Once the faulty section is corrected, the grid will automatically return the network to its original configuration.

Note that this feature to automatically close N/O points on feeders can only be activated on Port 1 of the 'T'-component, although faults on feeders will be isolated from both ends where the other end is connected to another 'T'-component with an FCL that disconnects the faulty network element from the other side.

Hence, this feature is also available in the 'T'-Smart grid, should operators want to use it.

In Chapter 5, simulated faults will be introduced into the 'T'-Smart grid to analyse how it would perform and solve network and energy constraints, and also to test the effectiveness of this feature. (The software for this function is explained in Appendix A.) These faults where introduced through a 'Fault Simulator' that breaks network connections without prior warning, as will be seen in Chapter 5.

4.5.4 FCL: ENABLING A DISCRETE SYSTEM

An important observation is that the FCL not only limits fault current amplitudes and fault propagation, but it also turns the management of the grid into a discrete system whereby the grid has a fixed amount of time to solve itself before action is required and taken.

This is because; while energy is stored in the FCL (by sources and energy storage elements with available energy) and load requests (including energy requests from energy storage elements) are received by the 'T'-components, the 'T'-components (with the certainty about the amount of energy sorted inside the FCL) and the grid's load requirements, then make the most optimal decision for the grid based on facts.

From Appendix A which explains the software code written to simulate the 'T'-Smart grid in Chapter 5, it would become evident that it is assumed that energy is stored for 0.01s (inside the FCL) and in that time the 'T'-Smart grid makes an optimal decision for the next grid state. Hence, each grid state comprises of 0.01s to charge and discharge energy from the FCLs and results in a minimum 0.01s delay from when electrical energy is generated until it is distributed into the grid. In the case of loads, energy requests are stored for a minimum of 0.01 s before supply is received. (Hence, an optimal grid connection decision based on the 'T'-Smart grid's rules is made by the 'T'-components while energy is still being stored inside the FCLs.)

Hence, there is never an unforeseen connection or disconnection (apart from faults) in the system as all the source availabilities, loading requirements and energy charging / discharging requirements of the grid and its components is known prior to connection thereof, which enables far superior management and distribution of energy in the grid.

4.6 PRIORITY ASSIGNMENTS

Numerous rules and functions may be defined by the Grid-operators of the Control-component to manage the grid, but some basic rules and functions are fundamental to the success of the 'T'-Smart grid.

The main function is the assignment of priority values to Grid-components and the way in which the 'T'-Smart grid then solves its states and configuration based on this. This will be expanded on later.

4.6.1 PRIORITY ASSIGNMENTS: SOURCES

First and foremost, loads must always be supplied from the highest priority sources first, where the network capacities allow it. This process of solving the grid then continues onto the next priority value of the Grid-components until the entire grid is solved.

Priorities of the sources are determined by numerous factors including the quantity and associated duration of energy it can generate, generation cost (capital, supply and maintenance cost), network location and available capacity of the network in its immediate vicinity, environmental impact, proximity to load centres (taking into consideration energy loss due to transmission and distribution of energy), economic sustainability, etc.

The Grid-operators will determine the weight of each factor to arrive at a final priority value and this calculation can be different between grids. Hence, the highest priority source will be the source with the highest score based on the factors deemed most important by the Grid-operators and will be determined upfront.

Thus each source will have its own unique priority number assigned to it in order for the grid to solve itself.

Note that a situation might arise where sources combine to supply a given load. Hence, assume energy have to be combined from two different sources to supply a given load and further assume that after adding the two sources together, an excess of energy remains after the load is supplied which is also not required elsewhere in the grid.

Firstly, the lower priority source will be reduced until the sources combined together match the load's requirements exactly. (This control function is explained in more detail in Appendix A.) Then, the source's energy is added together to supply the load, but the supply priority value communicated to the load will be calculated using the following pro-rata formula:

$$\text{Supply Priority} =$$

$$\frac{\text{Energy from source connected to grid port 1}}{\text{Total Energy supplied}} \times \text{Supply Priority of Source connected to grid port 1} + \frac{\text{Energy from source connected to grid port 2}}{\text{Total Energy supplied}} \times \text{Supply Priority of Source connected to grid port 2}$$

If more than two sources were used to supply a load, then each 'T'-component would use the above formula to calculate the pro-rata priority value of its two connected sources (connected to it) before sending the value onto the next 'T'-component which will combine the energy and priority value of the previous 'T'-components with its own energy source and associated priority value. This cascading calculation will continue until it reaches the load it needs to supply and then communicate to it the combined energy and supply priority value.

4.6.2 Priority Assignments: Loads

In the case of energy being supplied to numerous 'T'-components (which all supply loads), the highest priority loads will be supplied first, if the network capacity allows it. Else, it will be shed from the grid if the load requirement is greater than the available energy. However, the load may still be supplied if it is connected to a sub-grid which has stored energy available, as explained later.

Some of the factors that can be taken into consideration to determinate the load priority values may include the quantity of energy used, the time and duration of usage, environmental impact, network location and available capacity of the network in its immediate vicinity, load types (Critical: [Example] security, lights, heat, cooking. Non-critical: [Example] entertainment and loads that can be shifted to low peak times such as cleaning / washing machines.), proximity of sources (taking into consideration energy loss due to transmission and distribution of energy), etc.

Again, the Grid-operators will determine the weight of each factor to arrive at a final priority value and this calculation can be different between grids. Hence, the highest priority load will be the load with the highest score based on the factors deemed most important by the Grid-operators and will be determined upfront.

Unlike the sources, loads will be grouped into categories and each category will be assigned a different group priority value. Therefore, loads groups (types) are created and a specific load group (type) will be shed in a grid / sub-grid / portion of a constrained network, should the energy demand exceed the available network or generation capacity.

Thus, because loads are organised in different load category groups, load priority values are not unique and are automatically assigned once the load has been identified.

4.6.3 PRIORITY ASSIGNMENTS: ENERGY STORAGE ELEMENTS

Energy storage element will assume a load characteristic under charging conditions, and source characteristic under discharging conditions.

The same criteria as used for source and loads will be used to determine its priority value in addition to its energy storage capacity, charging rate, discharging rate, etc. and will be determined upfront.

However, the energy storage elements of the 'T'-Smart grid is intelligent and as will be explained later, can function in three different modes of operation.

Briefly, in its first mode of operation, it mainly functions as a component between a source and a 'T'-component and it stores excess energy not used by the main-grid. In such a scenario, it would not have its own priory value and it will simply take over the priority value of the source when interfacing with the main-grid. (This will be explained in detail later.)

Also, in its second mode of operation, it mainly functions as a component between a load and a 'T'-component and it intelligently requests energy from the main-grid such that it would almost consume a flat energy profile while the load connected to it can have a variable energy profile. In such a scenario, it would not have its own priory value and it will simply take over the priority value of the load when interfacing with the main-grid. (This will be explained in detail later.)

Hence, the priority values are only important when the energy storage element functions in its third and final mode of operation as explained later.

In this third mode of operation, the energy storage element intelligently determines the available energy and the load requirements of the main-grid, sub-grid, or sub-sub-grid it is connected to. It then stores excess energy not used by its grid and sub-grids connected to it, and only releases it when it is required by its grid or sub-grids connected to it. . (This will be explained in detail later.) Thus, it requires a unique priority value due to the fact that it can emulate a source when it supplies energy back to the grid, as explained later.

It always does this operation for grids connected to it, but never for grids above it, or to which it is connected. This is done in order to reduce the need for generation capacity and network infrastructure upgrades upstream in the network and this concept will be described in more detail in the sub-grid section explained next.

It should be noted that the 'T'-Smart grid is designed such that the priority values of loads and sources are considered before those of the energy storage elements, irrespective of the value. This is to ensure that the energy storage element receives its energy last and thus only receives the excess energy of the grid, and also that it supplies energy last so that its required storage capacity can be kept as small as possible and the maximum available energy from the grid is always used.

Also, irrespective of the source(s)'s priority that charged the energy storage element, when it discharges, it has a fixed unique priority value as explained earlier, independent of sources' or loads' priority values in the grid. Thus, the owner of an Energy Storage Element cannot profit from purchasing energy at a low priority value and selling at a priority, as then lower priority sources (such as non-renewable sources) can be sold at a fraudulent higher priority value. The 'T'-Smart grid does not allow this.

Instead, customers who have energy storage elements may be rewarded in other ways whereby their energy storage elements will reduce their energy demand profile such that it would be flatter (with less peaks) and this could lead to a lower energy tariff, if so determined by the Grid-operators.

4.6.4 Priority Assignments: Sub-grids

As mentioned in the previous chapter, the 'T'-Smart grid should only be an interim grid followed by facilitating back-up grid in future, once local generation sources and energy storage elements are fully developed.

Hence one would have pockets of sub-grids, sub-sub-grids, etc. being fully self-serviced and only relying on the main-grid as back-up supply. (The 'T'-Smart grid allows for sub-grids to be connected to sub-sub-grids, and also allows this inner grid functionality to continue indefinitely and would only be limited by communication requirements as with most Smart grids.)

To achieve this, from the main-grid's perspective, each sub-grid is assigned a source priority and load priority value as it may have sources, loads or energy storage elements connected to it. The source priority values are unique and the load priory values are not unique and both are determined and assigned values, as described earlier for normal sources and loads. Thus, the sub-grid is modelled as a single source or load (at a given time) in the main-grid and it alternates as system conditions in the main-grid or sub-grid vary.

The sub-grid is also set up such that it would only supply the main-grid with excess energy, should all its loads be supplied and its energy storage element be fully charged or unable to charge at the rate at which the source is generating electrical energy. This energy is supplied through the predetermined sub-grid source priority value to the main-grid.

Thus, when sub-grids supply energy, the sub-grid considers the main-grid as its lowest priority load automatically. This will then ensure that the sub-grid always supplies its own load first, before attempting to supply neighbouring loads as explained previously.

The sub-grid is also set up such that it would only take supply from the main-grid which is equal to the shortfall of energy required after all the generated sub-grid energy was used, and the sub-grid energy storage element is depleted or cannot discharge at the rate at which energy is required by the load in the sub-grid. This energy is received through the predetermined sub-grid load priority value from the main-grid.

However, when it receives this energy, the load in the sub-grid is then supplied by the main-grid's source and thus receives the energy with the original main-grid source's priority value. (This priority value may be a pro-rata value which was calculated from numerous sources, as described earlier.)

The previous explained then leads to a main-grid supplying the least amount of energy to the sub-grid with the smallest possible main-grid infrastructure. This then assists to bring main-grid costs and energy losses down.

This concept of forcing the creation of more sources closer to load centres always have a higher priority over other considerations including expansion of network infrastructure in the 'T'-Smart grid. It will be noticed that this 'rule' takes precedence over any other solving rule as described earlier and later and demonstrated in the next chapter. (Hence, even if a higher priority source exists in the main-grid, the local sub-grid's source would be considered first to solve the sub-grid's load requirement.)

Note that energy storage elements in sub-grids and main-grids can further assist to lower the need for upgrading the main-grid's generation capacity and network infrastructure, and this will only be explained later.

In addition, because there are two different priorities for when the sub-grid is reduced to a source or a load, it means that in the upper grid, some sub-grids may be considered before other sub-grids for supply. This gives a very powerful mechanism for grid controllers to receive energy from renewable sub-grid sources before non-renewable sub-grid sources and at the same time ensure more important loads are being supplied (which is driving the economy), before considering loads that can be shifted into lower demand times or are less important. Thus, a given sub-grid may have a high source priority value and a low load priority value, and all of this is determined by the Grid-operators.

4.6.5 Priority Assignments: Priority value adjustments

As described earlier, all priority values are determined upfront in order for the grid to solve itself. However, Grid-operators, through the Control-components, can still change these values to improve security of supply and grid performance based on off-line programs making use of optimisation algorithms or by user override under emergency conditions (if required).

In addition, threats to the grid which cannot be solved by 'T'-components on a feeder and Grid-component level, can be managed on a macroscopic level by changing the priority of certain Grid-components (by the Control-component) such that the grid would re-configure itself.

4.7 DEMAND CATEGORISATION AND DEMAND ZONE ASSIGNMENTS

Another important main function of the 'T'-Smart grid is the classification of demand into categories and the assignment of demand zones. Again, these rules and functions may be defined by the Grid-operators of the Control-component to manage the grid, and are again fundamental to the success of the 'T'-Smart grid.

In conventional one-way communication grids, where energy sources are few and generation capacity is quite large, customers are billed for the costs of using the shared network to transfer the energy from the generation station to the customer's loads.

These sources are a fixed distance from the customer which leads to a fixed Shared Network Cost. In a grid where there can be numerous sources feeding loads from different directions and distances (which can also change at any moment, i.e. come on-line or go off-line unpredictably); a cost needs to be calculated for the shared network that is to be used to supply a certain quantity of energy for a given time period.

The solution is to have pre-defined supply zones, from the 'T'-component connected to the load to the 'T'-component(s) connected to the source(s). There can be multiple zones, and the zones can be defined by distance or number of 'T'-components (nodes) up-stream / down-stream. For example, Zone 1 can be five 'T'-components to the left and two 'T'-components to the right of the 'T'-component supplying the load. Zone 2 can be four additional 'T'-components to the left and six additional 'T'-components to the right. This can be continued for an infinite number of zones.

In the next chapter, for simplicity, only two zones are selected where a load being supplied by a source in Zone 1 is referred to as 'In-zone' or else if it is supplied by a source in Zone 2 it is referred to as 'Out-of-zone'. (Hence, it is reduced to a logical 'In-zone' or 'Out-zone' function.)

Then, according to the predefined zones, as determined by the Grid-operators, the customers are billed only for the specific zone's Shared Network Cost (SNC).

However, the above only accounts for Shared Network Costs (SNCs) and not costs associated with generation capacity upgrades and infrastructure upgrades caused by peak demands.

According to [1], Smart grids that make use of dynamic tariff structures which increase in cost as the system's demand increases, have access to a powerful method for reducing the overall peak demand of the grid as customers are financially motivated to reduce their load.

However, apart from the fact that this system (in older installations of this system) currently relies on an average peak time instead of a real time system peak communicated to the customer, there are never costs allocated for if a sub-grid or feeder is experiencing peak demand irrespective of what the overall system is experiencing. Thus an infrastructure peak demand charge may be required by Grid-operators. (This will be demonstrated in the next chapter.)

Furthermore, additional costs may want to be included by grid-operates to loads, in cases where for example some customer's load had to be shed to supply the other customers' loads. Or if energy is procured from a neighbouring grid or sub-grid, which under normal healthy system conditions would not be used to supply any load in the local grid. Both these acts are referred to as an 'Intervention' and customers can be charged for this as mentioned. (Hence, it is reduced to a logical 'Load supplied without intervention' or 'Load supplied with intervention' function.)

It should be noted that only the main-grid / sub-grid that receives the energy is charged with the intervention cost and the grid supplying the energy is unaware of this event. This is to ensure that energy from the supply grid is not reduced or stopped by its operators wanting to store energy rather than to sell it to another grid, and, to ensure that the load grid obtains supply but at an increased tariff to so motivate its upgrade.

The above SNCs, peak demand costs and costs associated with interventions is combined in table 4.1 and it shows the different demand outputs the 'T'-component can give which represent a single or a combination of charges that may become applicable to a load (customer).

Table 4.1: Demand category assignments

Demand	**Zone**	**Intervention**
0 <= Demand <= 1	In-zone	Load supplied without intervention
1 < Demand <= 2	Out-zone	Load supplied without intervention
2 < Demand <= 3	In-zone	Load supplied with intervention
3 < Demand <= 4	Out-zone	Load supplied with intervention

In the first column, the demand of the grid at any point in time, communicated to the 'T'-component, is a percentage value of between 0% to 100% (or 0 and 1), where 100% (or 1) either means that there is no more generation capacity available in the grid or a feeder / sub-grid / grid has reached its maximum power transfer capacity.

However, as part of the communication strategy, the grid demand value is incremented (up to a numerical value of four) to signify whether a load is supplied from an 'In-zone' or 'Out-zone' source(s) and whether an intervention has occurred to supply the load as well. Thus, in both cases funding will be required to upgrade local sources / energy storage elements and network capacities and the customer(s) triggering this will then subsidize this through the increased Demand, Zone and Intervention charge strategy. Again, the grid controllers determine the weight of each factor and if and how much the tariff would increase for a given customer.

This grid demand value with its additional information as given in table 4.1 will be communicated to the loads or energy storage elements when in charging mode only. (Note that a grid demand value of between 0 and 1 indicates the source was 'In-zone' and no intervention occurred as shown in table 4.1.)

Sources and energy storage elements in supply mode will not be charged any SNCs in the 'T'-Smart grid as the costs of this is assigned to the loads in the network. The reason for this is to motivate customers to obtain their own energy sources and to save on this cost. (Hence, sources and energy storage elements in supply mode will be unaware if the loads were supplied 'in-zone' or 'out-of-zone'.) However, sources and energy storage elements in supply mode will be notified in the same manner as loads, if an intervention has occurred. (Hence, Grid-operators can decide if sources functioning in these periods should be rewarded additionally or not.)

As will be seen in the next chapter, the demand for each main-grid / sub-grid is calculated separately as it is functioning entirely on its own and the intervention charge mechanism is used to charge customers if energy is required from outside the normal functioning grid as explained earlier.

Also, as will be seen in the next chapter and previously explained, network feeder constraints can also result in separate demand calculations in a radially connected network, as feeder capacity constraints resulted in the grid's energy transfer being reduced, which then caused the available energy in a section of the grid to be reduced and the demand in that constrained section to increase. Hence, an infrastructure demand charge is then calculated based on this reduced availability of energy / infrastructure and overrides the grid's demand value, as explained under the FCL's limited energy transfer section.

Later, it will be described how and when these values are captured from the grid in order to accurately calculate these parameters.

4.7.1 ACTUAL SOURCE DEMAND

As can be seen in Appendix A and the next chapter, sources also record (without notification to the grid) their own demand separately and relative to itself. The difference between the actual source demand calculated (by the source) and that which is calculated by the grid, is that the actual source demand is a calculation relative to it itself and includes the initial demand of the energy used by the owner of the source. Thus, the 'T'-Smart grid allows sources to have more than one energy output, of which only one is connected to the grid and the other(s) are used by the owner / operator.

The grid's demand is only that demand which the grid experienced at the time when the energy was being supplied plus additional information on whether an intervention has occurred or not (without taking demand zones into consideration as explained earlier).

The actual source demand is therefore useful for the owner to determine whether it needs to expand its generation capacity or the demand information can be used for maintenance scheduling.

The grid's demand (with intervention alert) will impact on the compensation received by the owner of the source, from the grid, as determined by the Grid-operators. This can either be positive or a negative impact.

Currently in grids around the world, customers in high demand periods pay more for energy than lower demand periods, and hence one can argue that sources should proportionally be compensated for supplying energy in the almost 'emergency' period.

The author believes that this logic can lead to a situation where owners of energy sources may collude to only release their energy to the grid in peak periods and so push energy prices up to ultimately profit more from the system. Instead, it is believed that the compensation for the energy supplied from the sources must remain constant as the demand increases and especially when an intervention has occurred. However, whether to use this trigger or not, is determined by the Grid-operators.

All the above information is then captured and will be used to compensate the source for energy supplied based on the quantity of energy, duration thereof, the supply priority and the grid's demand at the time. (Again, Grid-operators can decide to omit or give more weight to any of these parameters, to better control and manage their grid.)

4.8 CONTROL OF ENERGY STORAGE ELEMENTS AND MODES OF OPERATION

As described earlier, energy storage elements interact intelligently with other Grid-components and it can either be connected between a 'T'-component and a source / load (series connection, first and second mode of operation) or just connected to the 'T'-component on its own (third mode of operation).

In the author's opinion, given adequate protection between sources, loads and energy storage elements, and if loads (and energy storage devices storing energy) would respond in a controlled manner to sources (and energy storage devices with available energy), then peak loading would not be a problem.

This management of Grid-components can be performed either before or after the system has reached its peak demand.

Management of the loading before the peak time entails a system whereby users agree in advance to the amount of energy and time it would be used. (Normally peak times would result in a higher energy tariff than then low peak times).

Or management of loading after the peak time entails simply increasing the cost of electricity, in real-time as the demand on the system increases. This management of energy might be a powerful technique of the ultimate future grid, but if used in isolation, would not give the required results.

Also, many believe that large energy storage devices (using potential energy, kinetic energy, chemical energy, electrostatic energy, electromagnetic energy, heat, etc. as storage medium) can also be a solution if space, weight, cost, efficiency and demand response problems can be overcome.

The 'T'-Smart grid aims to combine the previously mentioned solutions to achieve the goal of reducing peak demand.

By using a grid that increases the cost of electricity, as demand increases in real time, together with a large number of small storage elements (which can already be achieved making use of lithium-ion or super capacitor technologies) at individual customer level (instead of a small number of large energy storage elements connected at grid level), a reduced system peak load can be achieved.

This large number of small energy storage elements (at customer level) can also act as a grid energy back-up at customer, sub-network or main-grid level.

The communication and rules applied by 'T'-components to distribute energy and to avoid network overloading, as set up by the Control-component, will further assist in the energy management process as described earlier.

As discussed later, to ensure the system is even more effective, the 'T'-Smart grid will have the ability to manage energy from a large number of small distributed sources as well. Hence, ensuring distributed sources and distributed energy storage devices are closer to the distributed loads will ultimately solve the peak demand problems, grid network expansion problems, (possibly environmentally unfriendly) generation capacity expansion problems, and finally negate the need for a fully capacitated main-grid.

It should also be noted that as will be seen in the next chapter as part of an illustration, the energy storage elements only charge energy when there is an excess of energy in the grid. Similarly, it only discharges energy if all the available generated energy is used or there is a shortfall in energy to supply the load due to network constraints.

As will be described next, the energy storage element (independent of mode of operation) of the 'T'-Smart grid intelligently interacts with the 'T'-component and this feature is vital for the success of the 'T'-Smart grid.

4.8.1 ENERGY STORAGE ELEMENTS: FIRST MODE OF OPERATION

In the first mode of operation the energy storage element is connected between a 'T'-component and a source, and the energy storage element simply stores the energy which is not used by the grid at that point in time.

This effectively increases the source's supply capacity. Note however that the energy storage element loses its predefined unique priority (discussed earlier) and takes on the value of the source. (Hence the grid does not know there is an energy storage element connected to the source and it has no control over it. The energy storage element simply obeys the instruction of its owner / operator and ensures maximum benefit to the source it is connected to.)

The amount of energy stored from the source is dependent on the rate at which the energy storage element can charge and its saturation limit. If electrical energy is generated beyond these physical limits, (when considering renewable energy sources) and assuming the grid has sufficient energy already, then the energy would be lost as the energy storage element cannot retain it.

Conversely, it may be that a load is connected to the grid that requires more energy than what the sources have available and the energy storage elements' maximum discharge rates can release (assuming the energy storage element was fully charged before this event). Then, the grid will have to find more (internal or external-grid) sources and more energy storage elements to assist; else the load has to be shed.

4.8.2 ENERGY STORAGE ELEMENTS: SECOND MODE OF OPERATION

In the second mode of operation, the energy storage element is connected between a 'T'-component and a load, and the energy storage element is tasked to use a constant flow of energy from the grid and supply the load which may vary unpredictably in demand and have numerous high peaks and low consumption periods.

Similar prediction methods as those mentioned at the properties of the 'T'-component for source and load prediction can be utilised to manage the charging / discharging of the energy storage element. Hence, the rate at which the energy must be stored is a function of the predicted loading habits of the customer, which can be determined through a range of prediction methods based on historical loading data and other real time grid information.

This management system then ensures energy is always available while drawing an almost constant supply from the grid. Although a reasonably sized energy storage element will be required through conventional methods, an intelligent prediction system with minimal prediction error will limit the size substantially. (Hence, the 'T'-component which uses the same prediction system can advise on the size of the energy storage element required, to reduce peak demand, even before the energy storage element is procured.)

Note however again that the energy storage element loses its predefined unique priority (discussed earlier) and takes on the value of the load. (Hence the grid does not know there is an energy storage element connected to the load and it has no control over it. The energy storage element simply obeys the instruction of its owner / operator and ensures maximum benefit to the load it is connected to.)

The amount of energy that can be supplied to the load is dependent on the rate at which the energy storage element can discharge its stored energy (assuming energy is available) together with the available energy of the grid. If electrical energy is required beyond these physical limits, then the load will have to be shed.

Note that the energy request the energy storage element has made to the grid will be less than the required peak energy of the load, as some energy is discharged from the energy storage element to supply the load. The energy storage element is therefore required to draw an almost constant load profile continuously and not to relay peak energy requests to the grid, even if it is has no stored energy and cannot supply the load. (This will be expanded on later.)

Conversely, if the load request is less than the constant energy profile drawn from the grid by the energy storage element, then the excess energy is stored for peak energy requests times, which is more than the constant drawn energy profile.

Also, if the energy storage element is shed from the grid due to insufficient supply in the grid, then the load can only dependent on the energy storage element until all its stored energy is used (and the load is subsequently shed) or supply become available again.

As mentioned earlier, the constant load profile drawn from the grid is based on a prediction system that will automatically and intelligently ensure that that there is always sufficient energy available for the load while ensuring the most optimally sized energy storage element is used. This however is beyond the scope of this dissertation.

Hence, for simulation purposes in the next chapter, it is assumed that the constant load profile (or energy rate) that the energy storage element will request from the grid will always be 1% of the saturation capacity of the energy storage medium or 1% of the maximum charging limit of the storage medium, whichever is less. (This will be expanded on later.)

This assumption also assists in highlighting the problems a future Smart grid may experience if the constant load profile requested from the grid is incorrect. This will be further investigated in the next chapter.

4.8.3 ENERGY STORAGE ELEMENTS: THIRD MODE OF OPERATION

In the third and final mode of operation, the energy storage element is connected to a 'T'-component directly, which forms part of a sub-grid or main-grid. In this mode of operation, it stores excess energy available in the grid (after the other energy storage elements connected to the sources are saturated) and discharges energy when there is no more energy available (after the energy storage elements connected to the loads have fully discharged).

In this mode of operation, the energy storage element has its own unique priority (as discussed earlier) and the sub-grid / sub-sub-grid decides when to charge / discharge it. Hence, the owner(s) / operator(s) of the sub-grid / sub-sub-grid (which can belong to customer(s)) will always receive the maximum benefit from it.

Note however that if there should be excess energy available in the sub-grid / sub-sub-grid, and if the energy storage element(s) are connected directly to the sub-grid / sub-sub-grid (third mode of operation), then it would not impact on the demand of the grid if energy is taken from the grid and stored. The reason behind this is that if the energy was not stored, it would have been lost; hence it is omitted from the grid demand calculations. (This will be expanded on later.)

However, when the energy storage element discharges, it does impact on the grid's demand, because reserve energy (storage) capacity is decreasing (and it is modelled as a source in this instance).

From an operations perspective, the main-grid / sub-grid / sub-sub-Grid-operators will mostly benefit from these main-grid / sub-grid /sub-sub-grid connected energy storage elements if it is placed in strategic locations that would avoid future infrastructure upgrades caused by peak loading.

It should be noted that when an energy storage element is connected in this mode of operation on a given grid level, it is not only concerned about the energy excess or shortfall on that feeder or grid level, but also the levels below it, as long as the feeders to the sub-grid have spare capacity available to transport the energy.

However, when connected in a sub-grid / sub-sub-grid, the energy storage element will only assist that sub-section of network with excess and shortfall of energy and it would never supply energy to a higher grid level. Hence, owner(s) / operator(s) of sub-grid(s) can then store their own generated excess energy for use later when it may be needed, instead of selling it to the upper grid where it may be less beneficial for them. (i.e. Storing and using the energy by themselves is cheaper than selling the energy and later buying it back from the grid, at probably a higher price.)

The reason for this rule is to ensure that the main-grid and main-grid generators (mostly non-renewable sources) are always kept as small as possible and are only used as back-up energy sources. This rule then creates enough room for distributed resources to be used throughout the grid, without competition of the main-grid (and its generators), and more importantly, negates the need for expansion and upgrade of the main-grid network. This then in time can lead to the complete dismantling of the main (and current existing) grid. Hence, less money is wasted on upgrading and maintenance of the main-grid and its sources.

Note that whether the grid is experiencing an on-peak demand or off-peak demand, it doesn't affect this logic. This is because in future, due to the pricing incentives and customer energy management systems, the peak demand of the grid will be reduced but it may also become very difficult to determine whether a system is in on-peak demand or not, even with prediction models. Thus, this robust system will remain unchanged independent of grid conditions.

In future, from the grid perspective, if the grid has extra energy available (independent of on / off-peak time) it must have the ability to override a customer's decision not to buy electricity and store energy in a local customer's energy storage elements (if there is spare capacity available in the energy storage devices).

This is based in the assumption that this energy will be used in future, and whether it is used by the customer itself or his / her neighbour, moving the stored energy as close as possible to the load negates the need to upgrade network infrastructure and reduces the grid's overall peak.

Only after these devices are saturated with energy, can the local network and then the main-grid energy storage devices be considered for storage of energy. This solution does not profit the grid immediately (the order of energy storage will have to be reversed to achieve immediate profit) but will allow future cost saving by not having the need to upgrade the network. (This will also assist in the ultimate goal of making the grid a secondary source of supply.) Grid-operators and customers will have to decide together how the billing would work in such a situation. i.e. Will the tariff of already consumed energy be reduced, or will the grid still own the energy and only pay 'rent' to the customer for using their energy storage elements?

Further note that predicting the availability of renewable energy resources might be far more complicated when comparing it to the prediction of load profiles of customers. Thus, the reason for prediction the energy availability of local generation is to optimally reduce the size (and cost) of the required local energy storage element. In addition, the prediction of the local load and management thereof may further assist and have a greater impact on determining the exact size requirements. (These size requirements will reduce as energy availability and quantity of local sources increase.)

4.8.4 ENERGY STORAGE ELEMENTS: MODELLING

In the next chapter, an energy storage element is modelled for the use in simulations. One can read more about these and other components in Appendix A, however the following parameters defined for the energy storage element is very important and will be described. (There are also other less important parameters described in Appendix A.)

4.8.4.1 ENERGY STORAGE ELEMENTS: MODELLING: PERCENTAGE LEVEL DISCHARGE

Consider a circuit consisting of a single source and a load with the source capable of generating a given amount of energy ('X') and load requesting double the amount of that energy ('2X'). In this grid, the load would be shed as there is insufficient supply.

Now consider an energy storage element added to the grid that can store one hundred times the energy of the source ('100X'), then at the first state of the grid, the load will not be supplied and the energy from the source will be stored by the energy storage element ('1X').

In the second state of the grid, the energy from the source ('1X') will be added to the stored energy ('1X') to supply the load.

In the third state of the grid, the stored energy would have been fully used by the load and the grid will have the same properties of the first state. Thus, the load will be shed and all the energy from the source will be stored by the energy storage element. This pattern then continues indefinitely.

This leads to a problem where in a fast switching network, a load is only being supplied with energy every second grid state / period. Constant power loads cannot function effectively if it does not have access to a continuous energy supply. This can also lead to instability in the network.

The solution is to prevent the energy storage element from discharging as soon as it has energy capable of meeting the load requests. Rather, it must charge to a specified maximum charging limit before discharging. This level is defined as a percentage value of the saturation capacity of the energy storage element.

Conversely, this same parameter must be defined for the minimum discharge level before the energy storage element charges again. The model accounts for this minimum level as well. But this minimum value can also not be chosen too small, for example 0% (even if it is physically possible for the energy storage element), as then the same problem as explained previously can occur. This is because, it might only have a small amount of energy available which would not be enough to supply any load in the grid. Then it would charge and discharge as previously explained, around an energy level just above 0%. This level is also defined as a percentage value of the saturation capacity of the energy storage element.

As can be seen in Appendix A and the next chapter, the Percentage Level Discharge (PLD) parameter is described as:

[Maximum charging limit   Minimum discharging limit]

The first parameter is the maximum percentage of the saturation at which the energy level must be, before allowing the energy storage element to discharge.

The second parameter is the minimum percentage saturation level which the energy level can reach before it must stop discharging, until it has been fully recharged to its previous defined maximum charged level.

Note however that the energy storage element is designed such that it can charge energy at any given time and it is only its discharging which is controlled by this function.

The energy storage element's discharging function thus oscillates between these two levels. Assume the PLD is set to [100 10] value. Then the energy storage element will first charge to 100% of its saturation level (first parameter) before it discharges, and it will continue to charge (if extra energy is available) and discharge energy until the energy level falls below 10% of the saturation value (second parameter). Then, the energy storage element will only be allowed to charge (and not discharge) until the percentage saturation level defined by the first parameter, is reached. However, while it is busy in this second state of charging energy to the level of the first parameter, the grid will not receive any energy independent of whether the grid requires this energy or not.

It is again assumed that in future, a predictive system can optimize these two parameters (PLD) to ensure the smallest possible energy storage element is used.

4.8.4.2 ENERGY STORAGE ELEMENTS: MODELLING: CHARGE / DISCHARGE LIMIT

In order for the simulations in the next chapter to be as realistic as possible, a maximum charge and discharge rate limit is programmed into the energy storage element model.

This represents the physical limitations of an energy storage element's charging and discharging rates.

Even though these limits can be influenced by a range of factors including temperature, it is assumed to be a constant in the models and simulations of Chapter 5. (Note that these limits can be higher or lower than the limit of the FCL inside the 'T'-component. However, between these limits and the limit of the FCL, the lower value will determine the final charge and discharge rate.)

4.9 HIGH LEVEL SYSTEM CONTROL

This section briefly discusses the process flow of the 'T'-component, to solve a given grid state, as created by the FCLs. Thus, once all the available energy and load requests are known in the grid, because it is stored inside the FCLs, the grid state can be solved.

The reader can refer to Appendix A for a more in-depth discussion into the software programmed for the simulation models used in the next chapter.

Consider fig 4.11 which shows the overall high level control function of the 'T'-component.

At the start of a given grid state, the first step for the 'T'-component is to execute all the connections and disconnections as determined by the process performed during the previous grid state. This step is represented by the 'Execute decisions' block in figure 4.11.

The next step is to determine if faults have occurred in the network by making use of the node count function described earlier. In all the grids / sub-grids / sub-sub-grids where faults are detected, the N/O points are closed and the faulty section of the network is isolated.

Where there are no N/O points to close, the faulty section of the network is simply isolated. This step is represented by the 'Determine if faults in the network', 'Yes', 'Isolate and close N/O points' and 'No' blocks in figure 4.11.

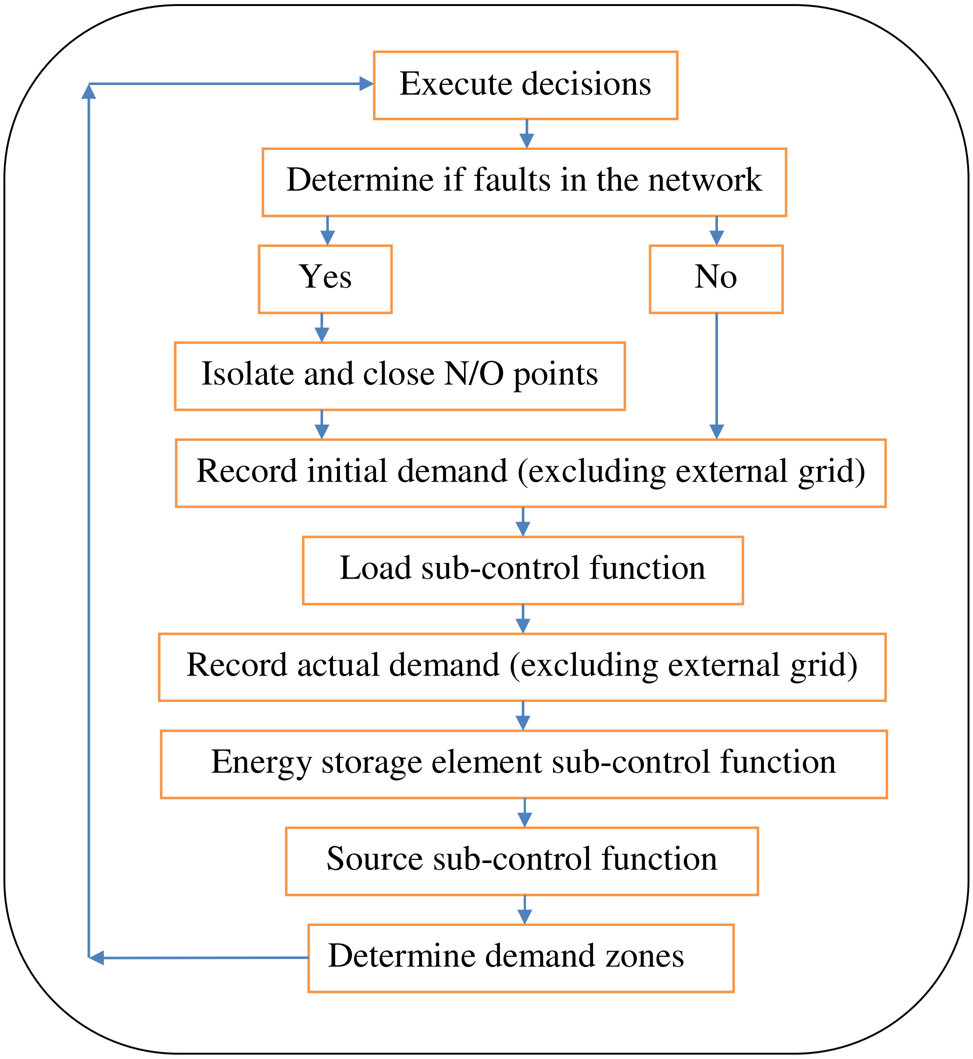

Fig 4.11: High Level process flow of the 'T'-component

Once the faulty sections of the network has been eliminated, the next step is to record the initial demand of the system without taking into account the energy assistance obtained from any external grid, for a given grid / sub-grid / sub-sub-grid. The reason for this is that, before external grids are used or loads are shed or energy storage elements are taken into consideration, the demand must be captured to determine if an intervention is required.

Hence, if at this step the demand exceeds the available energy then either load will have to be shed or energy from another grid will have to be acquired to supply the load. Either way, an intervention would occur and this function assists in recording this. This step is represented by the 'Record initial demand (without external grid)' block in figure 4.11.

The next step is to supply the different load categories and to shed load per category should the external grid, the available energy in the storage elements and sources be unable to supply the load. This will be expanded on later. This step is represented by the 'Load Sub-control function' block in figure 4.11.

The following step is to capture the actual demand of the system, again without the external grid. If the load requests still exceed the available energy, then the demand value is greater than one and it also means that energy from an external grid was used to supply the load. Then, the demand value is capped at one, to indicate no more energy is available in the local grid (or that the total available energy including that of the external grid matches the total load request exactly), and the demand value is also increased by a value of two, to indicate an intervention has occurred as explained earlier.

If the demand value is less than one, it means that load might have been shed in the previous step, and hence it must compare this calculated demand value with the one calculated two steps before, in order to determine if an intervention through load shedding has occurred. If this is the case, the actual demand value is simply incremented by 2 as described earlier. Finally, if no intervention occurred, the demand value is simply recorded. Once the final demand value (with or without intervention) is determined, it is communicated to all the Grid-components (sources, loads, and energy-storage elements). This step is represented by the 'Record actual demand (without external grid)' block in figure 4.11.

In the next step, the energy storage elements functioning in the third mode of operation is intelligently managed to either store or release energy. This will be expanded on later. This step is represented by the 'Energy storage element sub-control function' block in figure 4.11.

This step is then followed by considering all the available sources in grid. This is to determine if there might be more energy available than what the grid requires. Then certain source will have to be shed or its electrical energy generation reduced to meet the grid's load requests exactly. This will be expanded on later. This step is represented by the 'Source sub-control function' block in figure 4.11.

In the last step, all the demand zones are determined and only communicated to the loads and energy storage elements in charging mode, as described earlier. Thus, if a load is supplied by a source outside of its demand zone, then its previously communicated demand value is incremented by a value of one. This step is represented by the 'Determine demand zones' block in figure 4.11.

After this step, all the required decisions have been made by the 'T'-components and it can communicate all the energy, priority and demand values to the Grid-components and execute all the required decisions in the first step of the next grid state. (It should be noted that these values are only communicated between the 'T'-components and the Grid-components or sub-grids and not between the actual 'T'-components as stated previously. This is because the 'T'-Smart grid, as can be seen in Appendix A, makes use of a very efficient communication protocol where the minimum amount of information is communicated, and the previous mentioned values are all calculated by the 'T'-components from a few communicated parameters.)

Note that all the 'T'-components in the grid run this instruction set simultaneously and only controls the Grid-component connected to it, once the instruction set has reached the specific priority values which match those of the Grid-component connected to it.

4.9.1 LOAD SUB-CONTROL FUNCTION

Consider figure 4.12 which depicts the Load sub-control function process flow.

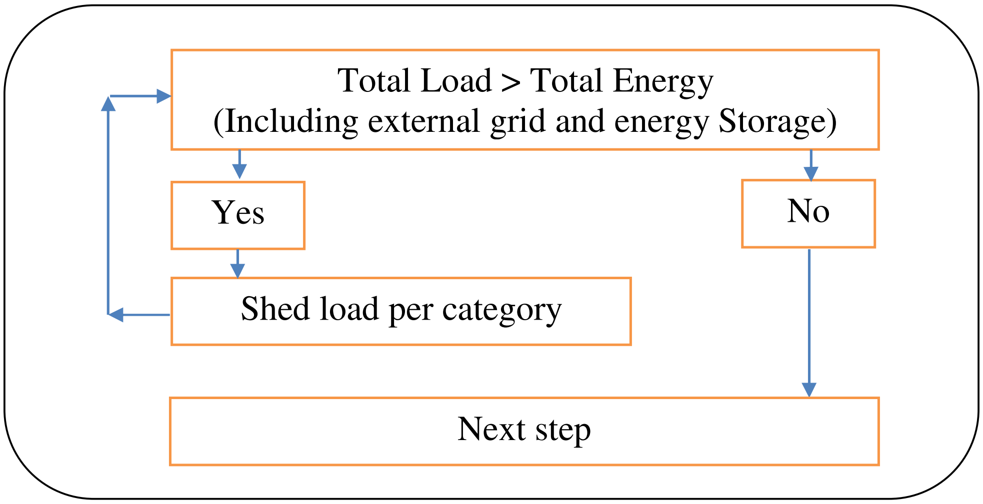

Fig 4.12: Load sub-control function: Process flow

The process simply involves checking whether the total load requests in the grid exceeds the total energy available.

The total load requests would include all the loads in the local grid, the load requests from energy storage elements functioning in the second mode of operation, and the load requests from the external grid. The total energy available will include all the local energy sources, energy available from energy storage elements functioning in the first and third mode of operation and energy from the external grid. Note that insufficient feeder capacity is the same as insufficient generation capacity to the 'T'-component as the available energy is reduced, as explainer earlier.

The sub-control function then simply sheds load until the available energy exceeds the total load requests. The external grid's load request is shed first followed by shedding load priority categories from lowest priority until the highest priority. Note that an energy storage element functioning in the second mode of operation, will emulate the priority of a normal load category as described earlier. Hence, it is considered a pure load and is shed as with the load categories defined by the Grid-operators.

Note that if external grids are not assigned the lowest source and load priorities, then local loads may be shed to supply external loads or local loads receiving power from external sources will incur extra network costs, and later this situation will lead to unwanted network infrastructure upgrade when in fact local source may be sufficient to supply the local load. This could also hinder external grids from acquiring their own sources, if a big portion of the external grid's energy requirements is met by a high priority source from the local grid. (Thus, there is no other choice but to minimize energy transfer to and from the external grid, to achieve the ultimate 'T'-Smart grid which comprises of many small grids with limited infrastructure and distributed sources and energy storage elements.)

Once the available energy equals or exceeds the total load requests, the process continues onto the next step.

Note that should the request for energy from an external grid be reduced or eliminated after this sub-control function, then this will be automatically updated before continuing to the next step. Hence, the least amount of energy (or exact difference between the available energy and the load request) will be requested from the external grid as explained earlier.

This is to prevent external grids from profiting and upgrading their infrastructure due to lack of distributed resources and energy storage elements in their grid. The grid customers will also be charged an 'Out-zone' charge to further assist in kerbing the upgrade of the external grid infrastructure and expansion of the feeders in the immediate vicinity of the external grid connection point as well.

4.9.2 ENERGY STORAGE ELEMENT SUB-CONTROL FUNCTION

Consider figure 4.13 which depicts the Energy storage element sub-control function process flow.

This process first determined if there are any energy storage elements that are operating in the third mode of operation. If there are none, it continues to the next step, else it continues with the process.

As part of the way in which the 'T'-Smart grid solves itself, all energy storage elements operating in the third mode of operation are assumed to be discharging all available energy in its initial state. (If it has no energy stored, it is assumed to be discharging zero energy. Thus, no energy storage element functioning in the third mode of operation is assumed charging initially.) Hence, it is expected that the total load would be less than the total energy as ensured by the previous process. However, the process re-calculates whether the total load is still less than the total energy if the external grid's source input is ignored. If the answer is no, then the external grid supplied the local grid and the total load matched the total energy available exactly, as ensured by the previous process and the process can automatically continue to the next step.

Note that the total load requests would include all the loads (not shed) in the local grid, the load requests from energy storage elements functioning in the second mode of operation, and the load requests from the external grid (if still applicable). The total energy available will include all the local energy sources and energy from energy storage elements functioning in the first and third mode of operation.

In the next step, if the total load request is still less than the total available energy (without accounting for the stored energy or storage elements discharging in the third mode of operation), then there is excess energy available in the grid and each energy storage element is checked per priority and changed from its initial state of discharging energy to charging energy. This process is continued from the lowest priority energy storage element up to the highest priority energy storage element until the total load requests match the available energy requests exactly or all the energy storage elements have been considered and the available energy in the grid still exceeds the total load requests. (Recall that energy storage elements can charge and discharge at any rate, within their limits as described earlier.)

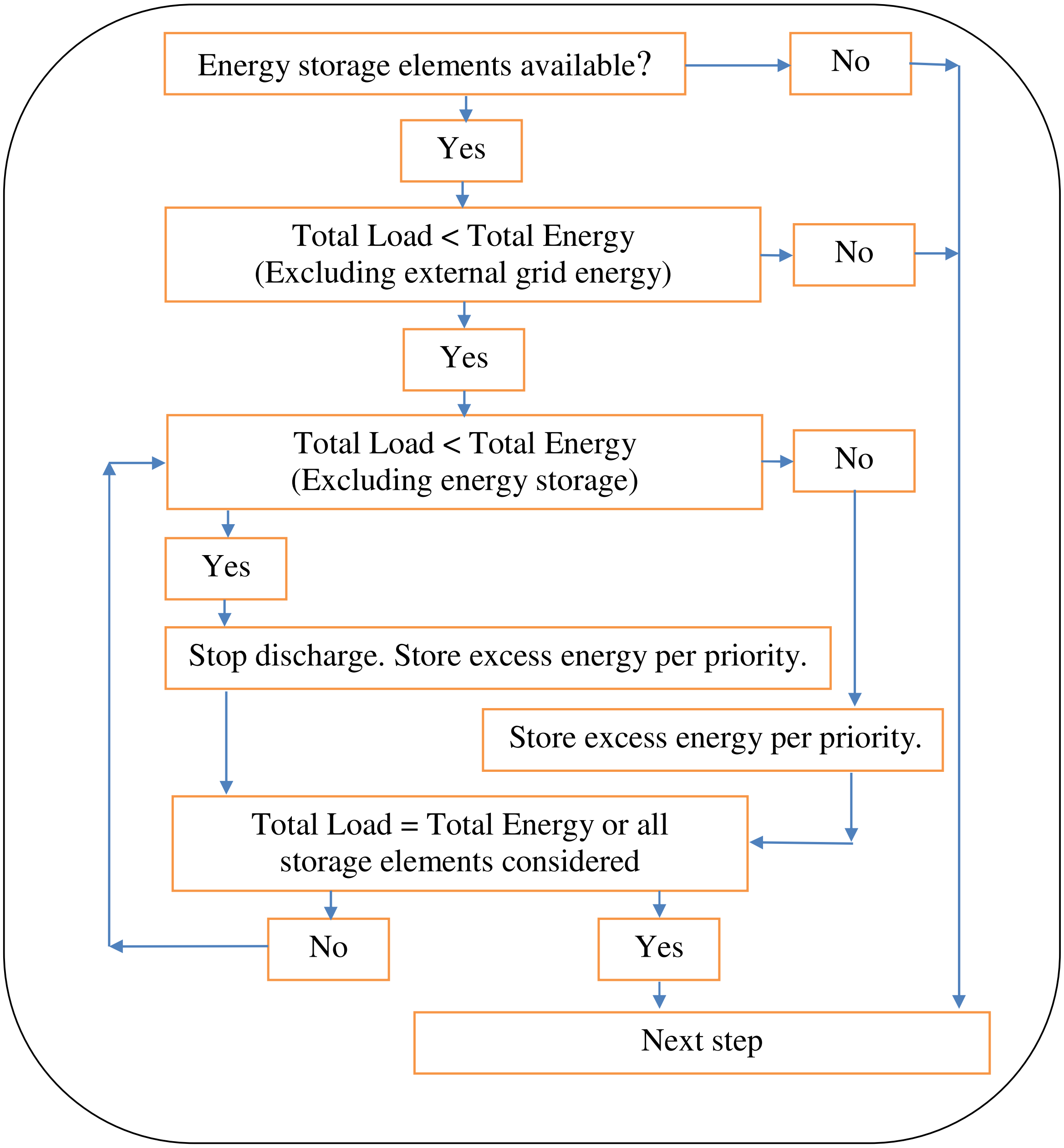

Fig 4.13: Energy storage element sub-control function: Process flow

If the total load request is not less than the total energy available (without accounting for the stored energy or storage elements discharging in the third mode of operation), then it means that some energy storage elements will be required to supply energy while others can charge energy. (Recall that the energy from external grid was previously eliminated.) Hence, the process will start at the lowest priority energy storage element up to the highest priority source and convert each discharging energy storage element to a charging energy storage element until the total load matches the total energy exactly or all the energy storage elements have been considered.

Once this is completed, the process continues onto the next step.

It is important to note that when the actual demand is captured before this step the energy storage elements are still being modelled as a source as indicated previously. Hence this lowers the demand value recorded and communicated to the loads as it acts as an artificial source.

Now, if there is excess energy, and the energy storage elements can store it, then this takes place after the actual demand was recorded. This means that the demand value communicated to the loads never reflect the effect of this. The reasoning is that this energy, if not stored, would have been lost, so it should not impact on the grid's communicated demand value as described earlier. (If this was not the case, and if there were energy storage elements with large storage capacities in the grid, then the demand would be unity for every state of the grid as unused energy will be stored and accounted for in the demand calculation.)

Hence, whether energy storage elements are charging (emulating a load) or discharging (emulating a source), it lowers the grid's calculated and communicated demand.

4.9.3 SOURCE SUB-CONTROL FUNCTION

Consider figure 4.14 which depicts the Source sub-control function process flow.

The process simply involves checking whether all the available energy in the grid still exceeds the total load requests. If the available energy matches the load requests exactly, then there it can simply go to the next step.

Else, each source from the lowest priority up to the highest priority will be checked and either the source will be shed or its generation capacity reduced. This process is continued until the total load request matches the new total available energy.

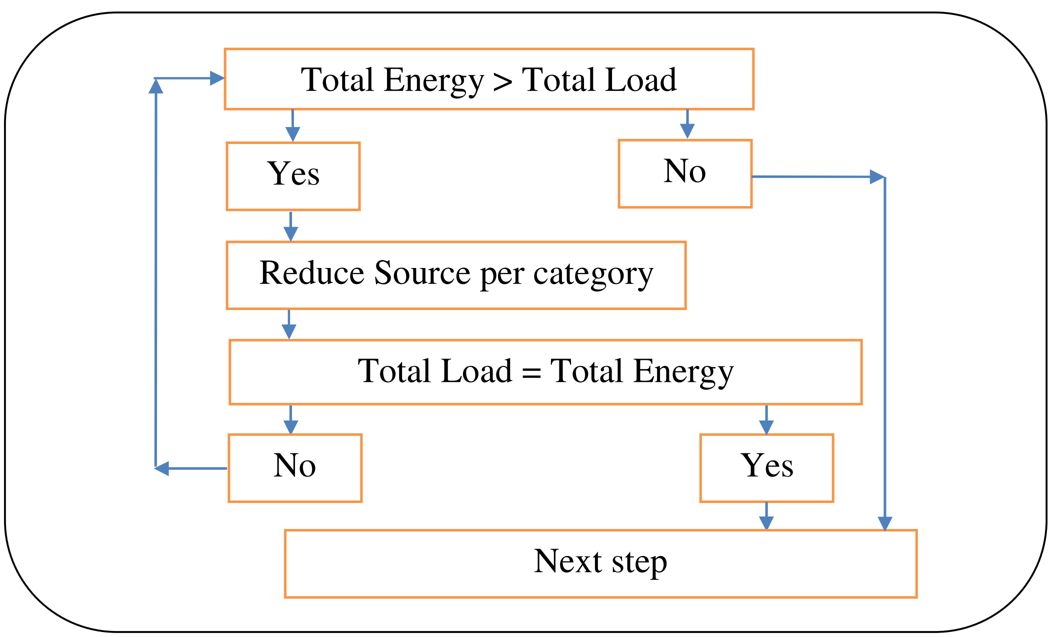

Fig 4.14: Source sub-control function: Process flow

Note that the total load requests would include all the loads (not shed) in the local grid, the load requests from energy storage elements functioning in the second and third mode of operation, and the load requests from the external grid (if still applicable). The total energy available will include all the local energy sources and energy from energy storage elements functioning in the first and third mode of operation. (Energy from external grids is excluded because if it was required, the total energy and total load would have matched earlier in the process and this step would thus have been omitted.)

Note that an energy storage element functioning in the first mode of operation, will emulate the priority of a normal source as described earlier. Hence, it is considered a pure source and will be shed or reduced as a normal source.

Once this is completed, the process continues onto the next step.

4.9.4 MODELLING

The reader is advised to consider Appendix A, which gives a high-level description of models created to simulate the 'T'-Smart grid.

As will be seen in Appendix A and the next chapter, the solution (control method) described earlier is executed in 100 time steps per grid state, such that a solutions or grid state is reached every 0.01 seconds. The previous mentioned process is thus repeated and after 0.01 seconds, and a new solution or grid state is reached.

Furthermore, it will be observed from Appendix A that all models have fixed states and a fixed set of instructions to follow as described earlier. All rules created have a definite fixed outcome and rules only get repeated once per simulation increment, per component model. Hence, the models and therefore the 'T'-Smart grid is stable and have predictable states.

However, it cannot be concluded or proven that the most optimum states will always be reached or that system cannot malfunction. If it does malfunction, it will not transport any energy from any source to any load.

In the author's opinion, this malfunction is unlikely as several models were created in Chapter 5, to not only display certain aspects of the 'T'-Smart grid, but also to show its ability to process and function under different scenarios.

As other possible grid configurations will only be an extension of the models created in Chapter 5, and since the fundamental models only function from fixed states and follow fixed instructions once, it can be concluded that the overall system should function as expected.

Note that executing final model instructions once per grid state avoids instability in the models which can only change state at each of the 100 increments inside a grid state or after an instruction is executed.

If there were an unfixed quantity of times the instruction set is executed, then this would lead to a scenario where models change state due to the instruction(s) and other models then respond with a new state. Once the same instruction set is executed again, the same first model sees other states in the other models (which was not there previously) and then changes its state again. This can then lead to a possible unsolvable cascading and infinite loop effect. Since the 'T'-Smart grid only executes a fixed set of final instructions every grid state, only once, this problem does not exist and the overall model is stable.

4.10 CUSTOMER BILLING AND ACCOUNTS

As customers may have sources, loads, energy storage elements and sub-grids (with the previous mentioned components), their credit / debit bill will be calculated as follows:

The credit bill for sources will consist of the of the quantity of energy generated and time of generation, the priority value of the source(s) involved, as well as the grid demand (with or without intervention) at the time of generation.

The debit bill for loads will consist of the quantity of energy used and time of usage, the pro-rata priority value of source(s) it was supplied with as well as the grid demand (with or without intervention) and grid zone value discussed earlier.

Energy storage elements will emulate sources or loads depending on its mode of operation and connection. It will thus be accounted for in the same fashion as sources or loads, depending on the mode of operation it is functioning in.

Hence, priority, usage time, duration and grid demand will all be factored into the bill to the customer, and Grid-operators can determine which parameter is applicable or not, or if a parameter would only constitute a factored weight in a final calculated value.

Hence, Grid-operators will have the full power to determine how tariffs are structured and based on the parameters customers are billed on, optimally manage and control their grid. All this applicable information, recordings and calculations will then be summarised and included into one bill to the customer.

Also, as described earlier, Grid-operators can also consider rebates to customers who have energy storage elements or even lower tariffs to customers who have a relative flat loading profile.

Note that all though the 'T"-component will gather all this information and communicate it to the Control-component, as mentioned earlier, the Control-component will be ultimately responsible for managing customer billing. (This information will also be recorded and stored by the Control-component so that is can be used in several off-line functions as described earlier.)

4.11 ABRIDGED SUMMARY AND GENERAL CONCLUSION

The 'T'-Smart grid concept comprising of a Control-components, 'T'-components and Grid-components was discussed in this and the previous chapter. The 'T'-Smart grid aims to ensure sufficient interaction between utilities and customers such that an energy trading market can be created in future with distributed energy sources and energy storage elements, while ensuring complete protection between all the Grid-components.

The chapter started with an example to explain the 'T'-components' basic operation which took into account network configuration and source availability.

It was followed by the 'T'-component properties of which the most important was to:

- ✓ Ensure seamless integration between, and management of, an unlimited number of Grid-components (sources, loads and energy storage elements) in the main-grid and sub-grids such that network capacity constraints and peak loading will be minimized and,

- ✓ Ensure complete electrical protection between all Grid-components and sub-grids by eliminating the propagation of fault currents and limiting fault current amplitudes (to reduce associated infrastructure fault capacity upgrades and earthing requirements).

The 'T'-component (of the 'T'-Smart grid) was further analysed and can be described as a three port power transfer component of which two ports are connected to the grid and the third to the Grid-components and sub-grids. Each grid connection port can either be an input or output, enabling the 'T'-component to combine energy from two different sources to supply a load, to split energy from a source in two different directions or, to add (if a source) or subtract (if a load) from energy flowing through the 'T'-component.

Inside the 'T'-component, one can find a novel Fault Current Limiter (FCL) that temporarily charges energy from the grid and discharges energy to the grid, in a small internal temporary energy storage element. This not only allows fault current amplitude to be limited (due to limited storage capacity of the temporary energy storage element), but the FCL can be controlled to emulate different output voltage signals (as required by the grid) and also, the rate at which the FCL discharges can be used to detect faults in the grid.

The proposed internal layout of the 'T'-component comprises of voltage- and current-transformers (to sense different voltage signals and for protection purposes), many FCLs making use of switches (to limit fault current amplitude and propagation, and assist with other functions), isolating and earth switches (for maintenance on feeders and the 'T'-component), an internal control computer and, a communication link to Grid-components, other 'T'-components and the Control-component.

Because the FCL has limited energy storage capacity, it can impact on the demand of a grid / sub-grid / sub-sub-grid or portion of a radial grid, as the effective available energy is reduced which leads to an increase in demand. (It also limits the 'T'-components' energy capacity.) This same effect can be the result of a constrained busbar or feeder in the network (hence, all the elements should be matched), and the increased profit obtained from customers using energy in peak time (assuming a tariff which increases with demand), can be used to subsidise the network upgrades.

The 'T'-component also has the ability to close N/O points in the network once a fault is detected in the network (with the help of the FCL). The 'T'-component simply detects the number of 'T'-components connected to it, compares it to a pre-programmed value, and if it becomes aware of a missing component, it would perform the necessary network isolating and earthing procedure and close N/O points in the network, if available.

Because energy first needs to be stored inside an FCL, before it can be discharged, it creates a grid with discrete grid states (similar to a sampler in an analogue to digital converter). This grid state (expanded on later) created by the FCL allows it to charge and discharge energy as determined by the control process in the previous grid state and to optimally solve the grid's next state, as all the available energy and load requests are known.

In the 'T'-Smart grid, all the Grid-components are assigned priority values and in the control process, Grid-components are assisted in the grid in the order from the highest to the lowest priority. Energy sources (or energy storage elements discharging energy) may combine energy and priority values (in a pro-rata manner) to supply loads.

Energy sources and energy storage elements operating in the third mode of operation have unique priorities, unlike loads which are divided into unique load categories as each load does not have a unique priority value assigned to it. (Energy storage elements operating in the first and second mode of operation, which emulates sources and loads respectfully [as summarised later], takes on the priority value of the source or load connected to it.) Sub-grids and Sub-sub-grids are assigned a unique source priority value and a unique load category priority value and are reduced to an equivalent source or load in order for the main-grid to solve it. Based on several considerations, Grid-operators assign specific priority values to the Grid-components.

Sub-grids and sub-sub-grids of the 'T'-Smart grid is programmed to only allow the minimum amount of energy from the main-grid to assist it and will always first utilise its own energy sources and storage elements. This then reduced the need for a main-grid and allows for many small distributed sub-grids with their own energy sources and storage elements as the 'T'-Smart grid intended.

Grid-operators, through the use of the Control-component, may still change any priority values (at any stage) to optimise the grid or during emergency conditions, as required.

Using priority assignments are only one technique to manage the grid and control (limit) peak demand. (I.e. if the load requirements exceed the available energy in the grid, then loads are shed by category rather than sections of the grid.)

Another technique of the 'T'-Smart grid to reduce peak demand and reduce the need for infrastructure upgrade includes:

- ✓ Billing loads and energy storage elements in charging mode a demand zone charge which is an accurate shared network charge calculated in real time based on the exact network used at that time (for a specific load) to transport energy from a source(s) to the load. This should motivate customers to consider more local energy sources and energy storage elements rather than to prolong the use of the main-grid.

- ✓ Notifying Grid-components that an intervention occurred. An intervention has occurred when load was shed to supply another load or when energy was acquired from an external grid. (Note that sources and energy storage elements in discharging mode are also notified, so that they can be rewarded for supplying energy during this time, if Grid-operators require this function.)

- ✓ Taking into consideration network capacity constraints and increasing the demand accordingly, as the energy transfer is constrained and the available energy reduced (due to the network) resulting in an increase in the demand. This increased demand is communicated to all Grid-components.

Furthermore, energy sources record a separate demand value relative to itself to assist source operators with capacity upgrade and maintenance planning.

Grid-operates may decide that energy sources supplying energy in on-peak times or during an intervention, receive more financial compensation. However, in the author's opinion, it is believe that this could create a platform for source operates to abuse the system and only release energy when the demand and subsequent tariff is at its highest. Therefore, compensation for energy supplied by sources should be independent from the grid demand or whether an intervention occurred or not.

Another aspect of the 'T'-Smart grid to reduce peak demand and the need for infrastructure upgrades, is the implementation of numerous energy storage elements throughout the grid which intelligently interacts with the 'T'-Smart grid and other Grid-components. The energy storage elements can operate in three different modes of operation and functions as follows:

- ✓ In first Mode of operation, the energy storage element is connected in series between a source and a 'T'-component. The object is to store excess energy not used by the grid and effectively increase the source's supply capacity.

- ✓ When in the second mode of operation, the energy storage element is connected in series between a load and a 'T'-component. The object is to draw a constant energy profile from the grid, while the load connected to it varies unpredictably in supply requirements.

- ✓ If the energy storage element is connected to the grid / sub-grid / sub-sub-grid alone, it functions in its third mode of operation. The object is to store excess energy (after other energy storage elements functioning in the first mode of operation are saturated) and to discharge energy (after other energy storage elements functioning in the second mode of operation have fully discharged), intelligently in the grid.

The 'T'-Smart grid has the ability to control a large number of energy storage elements and energy sources. This will ensure that distributed energy storage elements and sources can be installed closer to the load centres which will assist in reducing peak demand, infrastructure upgrades, and the need for a fully capacitated main-grid.

Many parameters are defined to control the energy storage elements in order to ensure realistic simulations in the next chapter. Although all these parameters are explained in Appendix A, two parameters are important:

- ✓ The first parameter is referred to as the 'Percentage Level Discharge' parameter and its function is to intelligently control the release of energy to the grid such that it would not cause instability.

- ✓ The second parameters, 'Charge limit' and 'Discharge limit' simulates the physically limitations of the energy storage elements to charge and discharge energy at a given rate.

Based on the priority values of the Grid-components explained earlier, the 'T'-Smart grid solves itself and it controls the amount of energy added, released and distributed in the grid. An eight step high level process to control the grid is followed which repeats continuously:

- Firstly, it executes all the decisions (connections and disconnections) determined from following this process in the previous grid state.
- Secondly, the 'T'-Smart grid checks for faults in the network and subsequently isolates the faulty sections. N/O points (for back-up supply) are also closed if available.
- Thirdly, the initial demand of the network is recorded to determine whether an intervention is required.
- Fourthly, load is shed per category (from lowest to highest priority, if required) until the total available energy matches or exceeds the reduced total load. During this step, the minimum amount of energy is requested (if required) or the maximum amount of excess energy is supplied, to the external grid.
- In the fifth step, the actual demand of the grid is captured (taking into consideration network constraints) and the demand value is incremented if an intervention occurred.
- In the sixth step, all the energy storage elements functioning in the third mode of operations are considered. As part of the control process, all these energy storage elements were initially set to discharge energy (if available). In this step, all energy storage elements are considered from the lowest priority to the highest priority, and its initial discharge setting is changed to a charge setting if excess energy is available. This is done for all the energy storage elements until the available energy matches the total load and energy charging requirements exactly, or all energy storage elements have been considered and there is still an excess of energy.
- In the seventh step, all energy sources from the lowest to the highest priority are considered. If the total available energy matches the total energy requirements, then the process can continue to the next step. Else, sources are shed or reduced until the remaining available energy matches the remaining energy requirements exactly.
- In the eighth step, the demand zones ('In-zone' and 'Out-zone', for SNCs) are determined for the loads and the demand values are subsequently incremented as required. This is followed by communicating all the energy, priority values and demand values (which accounts for network constraints, interventions and demand zones), to the Grid-components. (This is done through an efficient communication protocol, as can be seen in Appendix A, to reduce the impact that communication limitations may have on the 'T'-Smart grid. Also, many values are calculated rather than communicated, to assist even further.) The decisions and calculated values of this control process is then stored (inside the 'T'-component) so that at the start of the next grid state, all these decisions can be executed and the values be made available to the customers.

The reason why the 'T'-Smart grid has the ability to optimally make decisions is that the energy from sources and energy storage elements, and energy requests from loads and energy storage elements, are stored in the FCLs before a solved grid state is reached. This enables the 'T'-Smart grid to make decision based on real time facts and the reader can refer to Appendix A for more information. This process would result in a solved grid state every 0.01s as seen in the next chapter as part of the simulations.

The 'T'-Smart grid-component models (used in simulations in the next chapter) all have fixed states with a fixed set of instructions to follow which lead to a fixed and predictable outcome. These instructions sets, of all the Grid-components, from the lowest priority to the highest priority, get executed only once per grid state to ensure the 'T'-Smart grid is stable. However, it cannot be proven that optimal states will always be reached where the worst case is that Grid-components are simply disconnected. In the next chapter, several simulated grids are tested to illustrate the functioning of the 'T'-Smart grid and to prove its robustness in a varying grid.

Finally, the information gathered from the 'T'-components are communicated to the Control-component which is responsible for issuing customers with credit / debit accounts. These accounts will consider the sources / loads / energy storage elements connected to the grid, the priority values, demand values, duration of connection, and energy quantities, etc. to promote and establish a platform for a future energy trading market. Grid-operators will determine the weight of each factor in order to effectively manage and control their grid.

Grid-operators may also choose to reward customers even more for having an overall flatter energy consumptions profile, rather than reducing their average loading.

The ultimate aim of the 'T'-Smart grid is to reduce peak demand through the various physical components and management rules, energy charges and incentives, and to kerb the expansion of the main-grid. This can be achieved by moving Grid-components closer together to create pockets of sub-grids which only utilise the main-grid as a back-up supply. The main-grid does not profit from this directly, but gains indirectly as costs associated with network expansion and maintenance is reduced. As mentioned in the previous chapter, the 'T'-component is designed to facilitate this transition and final phase of the future Smart grid and to meet the requirements and problem statement described in Chapter 1.

CHAPTER 5: 'T'-SMART GRID SIMULATIONS AND RESULTS

5.1 INTRODUCTION

This chapter gives examples and documents results of how the 'T'-components interacts with other Grid-components and sub-grids, in a few simulated distribution grid scenarios. In the author's opinion, future Smart grids as a minimum should be able to meet or better these results and performance measurements in order to evolve to Smart grid that fulfils the requirements of [1]. It will also be shown that the 'T'-Smart grid addresses the problem statements and objectives mentioned in Chapter 1.

All models and software were created in (Matlab) Simulink. The results from the models in Simulink were recorded and displayed in Matlab. Please refer to Appendix A for more information.

The examples to be discussed in detail in this chapter is summarised below. It aims to show how the 'T'-Smart grid functions under different grid scenarios. This is done to show the unique capability of the 'T'-Smart grid. The examples are:

- ✓ Example 1 - A source and a Load; shows how sources and loads interact without the presence of a grid.
- ✓ Examples 2 - Sources only; shows how sources in a 'T'-Smart grid would operate alone.
- ✓ Example 3 - Loads only; is the same example as Example 2, with loads connected to the 'T'-Smart grid alone.
- ✓ Example 4 - Three sources and a load; shows how the priority values of the Grid-components can be varied by the Control-component and how the 'T'-Smart grid would solve itself (based on this) without the need of any external influence.
- ✓ Example 5 - Sub-grids, Demand zones and Interventions; illustrates how customers can be charged for SNCs and interventions, as explained in Chapter 4.
- ✓ Example 6 - Increased demand due to infrastructure constraints; demonstrates how the 'T'-Smart grid adapts to infrastructure limitations in an optimal way.
- ✓ Example 7 - Dividing energy in a constrained network; is a follow up example of Example 6 and further expands on this matter.
- ✓ Example 8 - Energy storage element's first mode of operation; illustrates this operation as explained in Chapter 4.
- ✓ Example 9 - Energy storage element's second mode of operation; illustrates this operation as explained in Chapter 4.
- ✓ Example 10 - Energy storage element's third mode of operation; illustrates this operation as explained in Chapter 4.
- ✓ Example 11 - Energy storage element in a sub-grid, demonstrates an important property of the energy storage element to ensure that excess energy from the sub-grids are stored and discharged when necessary, without assisting the main-grid connected to it when the sub-grids require the energy.
- ✓ Example 12 - A fault on a radial network; shows how after a fault, two radial networks can be solved together as one radial network, automatically by the 'T'-Smart grid.

- ✓ Example 13 - A fault on a ring network; further explored this function and solves a ring network (with an N/O point) in a different way due to a fault that occurred in the network.
- ✓ Example 14 - A fault on a ring connected sub-grid; also follows on the previous examples and shows how a sub-grid ring network can connect Grid-components at two different 'T'-components on the main-grid.
- ✓ Example 15 – Versatility of the 'T'-Smart grid; is the final example which shows how the 'T'-Smart grid can reconfigure a sub-grid to be connected as a radial connection to the main-grid, due to a fault and still solve the new grid successfully.

A summary of notes (from Appendix A) is given below in order for the reader to understand some of the concepts not mentioned in the previous chapters.

- Energy is supplied, transported and consumed at each increment of time throughout the 'T'-Smart grid. It is this energy that is displayed as the 'signal values' in the graphs to follow. The reason for this is that the FCL system divides the available energy and transports it throughout the grid and thus a non-continuous signal would indicate a malfunction of the 'T'-Smart grid. The graphs thus show the amount of available energy generated, distributed (by the FCLs) or used for each time increment of the simulation. (Consider Appendix A for more information.)
- If a Grid-component is disconnected from the grid, its signal / energy value will be zero and its priority values and demand values will be assigned a '-1' value by default. This is done in order to distinguish from such scenarios where Grid-components may have zero priority values or where the grid's demand may be zero.
- Grid-component values (shown on outputs graphs of examples) are simply numerical value assigned to Grid-components so that the 'T'-components would know whether a source, load or energy storage element functioning in the third mode of operation is connected to it. Consider Appendix A for more information.
- In the examples to follow, the term energy supplied, used or transported is used for time intervals (fixed periods) and can be considered to be equivalent to apparent power or real power (as the 'T'-Smart grid would correct the power factor of all the signals) over that period. Thus, in the explanations of the examples, the term energy is used, as for a given time interval the energy being accounted for is the amount of real power supplied, used or transported over that time interval.

5.2 EXAMPLE 1 - A SOURCE AND A LOAD

The first example demonstrates how the different component models can function on their own, without a 'T'-component, as in the practical world. Consider a source connected to a load as shown in figure 5.1.

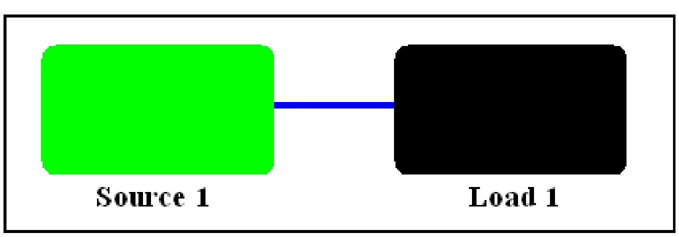

Fig 5.1: Simple representation of the circuit - Example 1 - A source and a load

As can be seen from figure 5.2 and figure 5.3 (Example 1), the source can deliver 10 units of energy constantly, and the source's assigned priority is 5, with no other internal loads which could have affected its initial demand (see Chapter 4 for more details).

The load however requests first 7.5 units of energy for the first second, and then 15 units of energy for the second simulation second. Its load priority is 5, but this would not make a difference as it is the only load in the circuit.

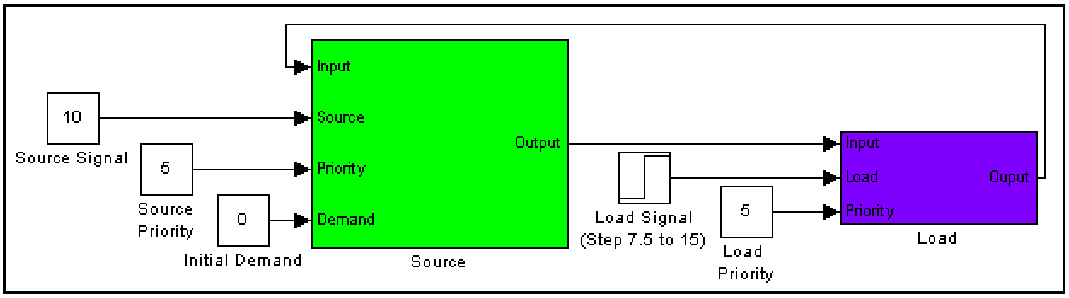

Fig 5.2: Simulink representation of the circuit - Example 1 - A source and a load

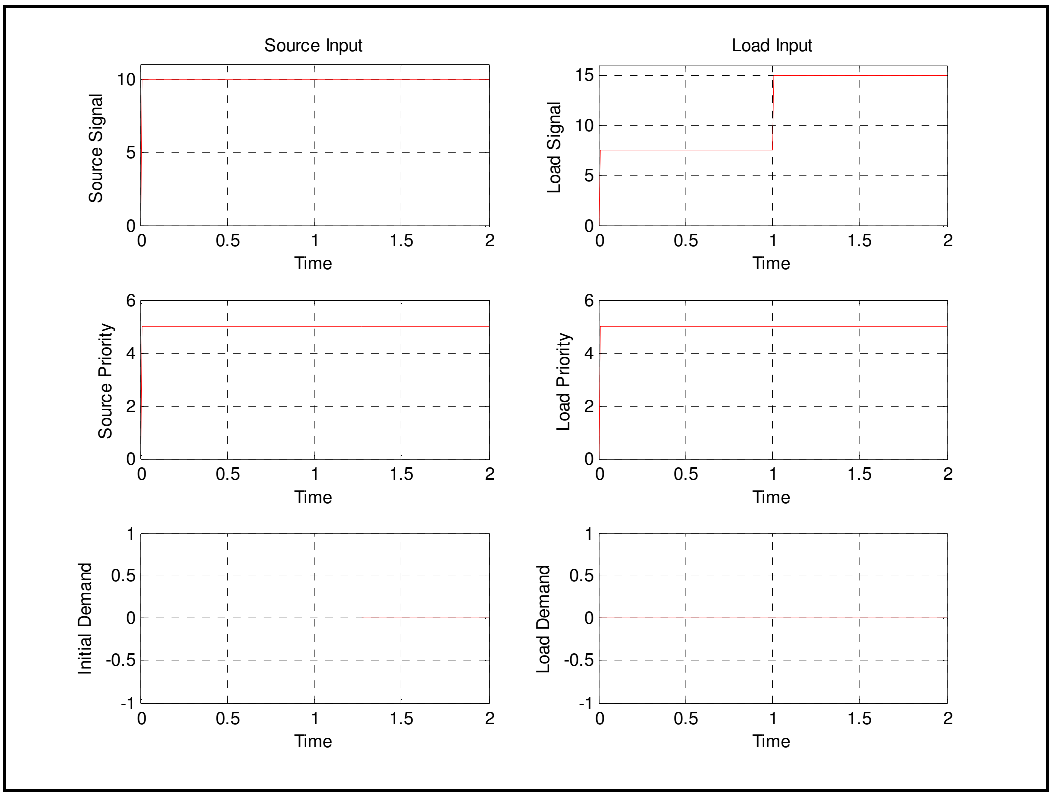

Fig 5.3: Inputs to the circuit - Example 1 - A source and a load

Finally, the load's demand is 0, because energy is only now being requested and prior to the simulation, the circuit can be considered as disconnected. (This is true for all loads in other simulations.)

From figure 5.4, focus on the first column showing the source's simulated results. It is noticed that the source supplied 7.5 units of energy to the load for the first simulated second, after which it couldn't meet the loads requirements and shut down after this. While it was still supplying the load, its supply priority was 5 and according to the source, the grid's demand was 0. The reason for this is that there was no 'T'-components in this circuit, so in actual fact there was no grid. Thus, as 'T'-components determine the grid's demand, in its absence, the grid demand was zero.

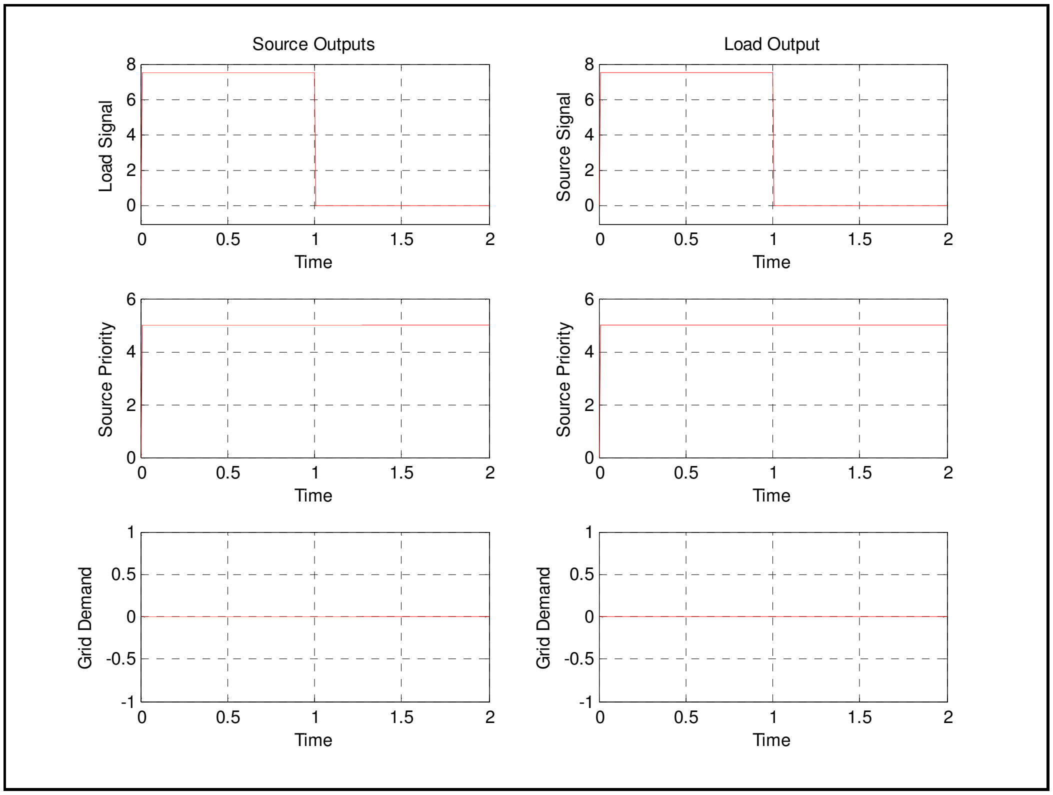

Fig 5.4: Outputs of the circuit - Example 1 - A source and a load

The above parameters of energy units supplied or used, priority of source, and the grid's demand is recorded for each customer and a bill is generated from this as explained in the previous chapter. Hence, the owner of the source would be credited for energy supplied and the owner of the load would be debited for the energy used. (This remains true for future examples as well.)

Note however, the owner of the source still needs to perform maintenance (and capacity upgrade planning) on its generation equipment and because of that, the source's internal demand is recorded as explained in the previous chapter. The results of figure 5.4, is known to the Grid-operators and grid's billing systems, however, the results from figure 5.5, is only known to the owner of the source.

In figure 5.5, the internal demand was recorded as 0.75 because the total available energy units were 10 and the load requested was 7.5. Hence the internal demand was 7.5/10 = 0.75 (for the first simulation second). Note that if it had an initial demand, then this would have affected the results and it would be evident that the source was supplying more than just the load shown in figure 5.2. (Also note that this recorded demand value is not affected by interventions, constrained networks and demand-zones and retains a value of between zero and one. This is unlike the grid's demand values as will be seen in later examples and explained in the previous chapter.)

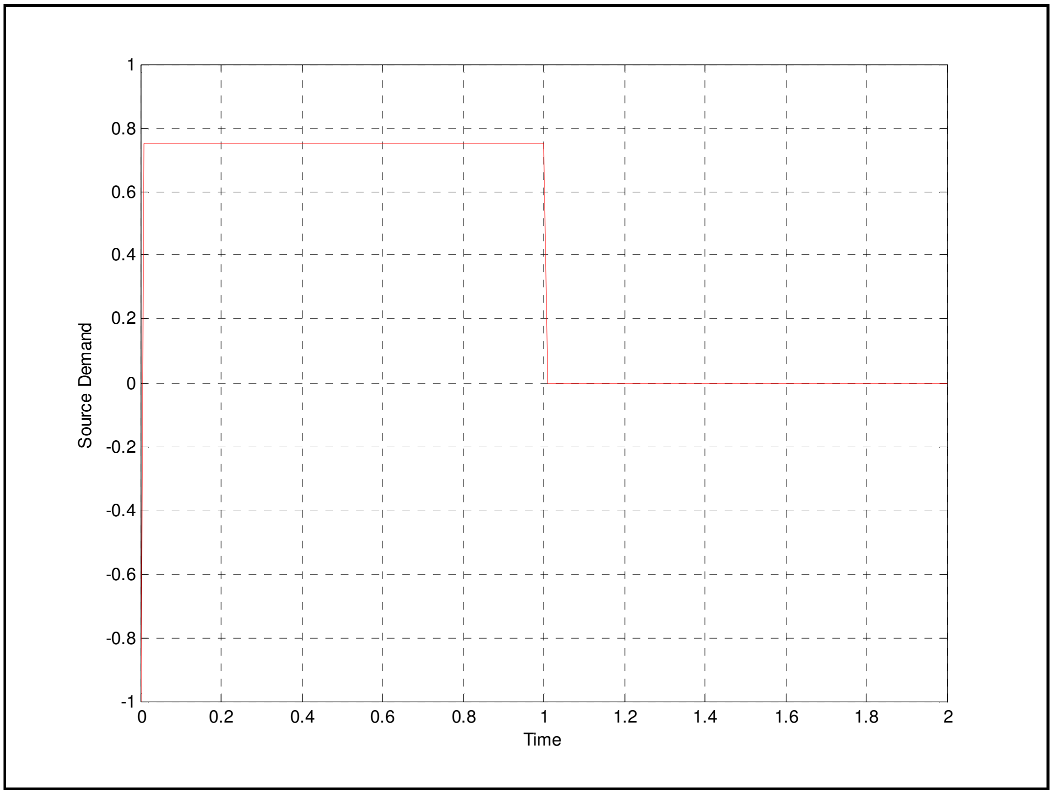

Fig 5.5: Outputs of the circuit - Demand of Source 1 - Example 1 - A source and a load

5.3 EXAMPLE 2 - SOURCES ONLY

The second and third example aims to demonstrate the stability of the 'T'-Smart grid's control process. Consider figures 5.6 to figure 5.9 which shows three sources connected together through three 'T'-components.

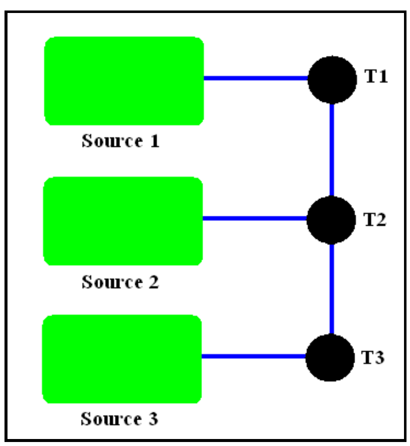

Fig 5.6: Simple representation of the circuit - Example 2 - Sources only

In figure 5.8, it is noticed that all three sources supply the same amount of energy (10 units) to the grid, but at different priorities of 5, 10 and 15 respectively. And all initial demands, for this example, were set to zero.

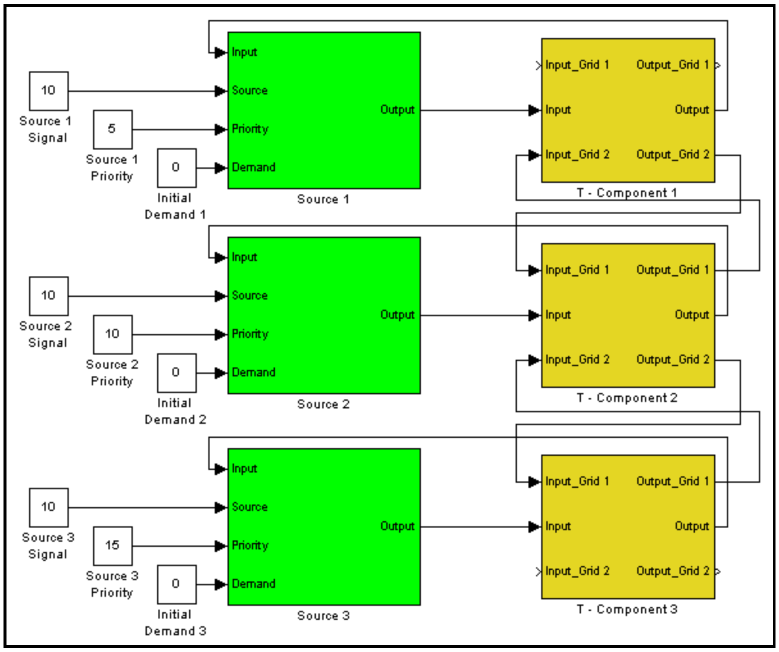

Fig 5.7: Simulink representation of the circuit - Example 2 - Sources only

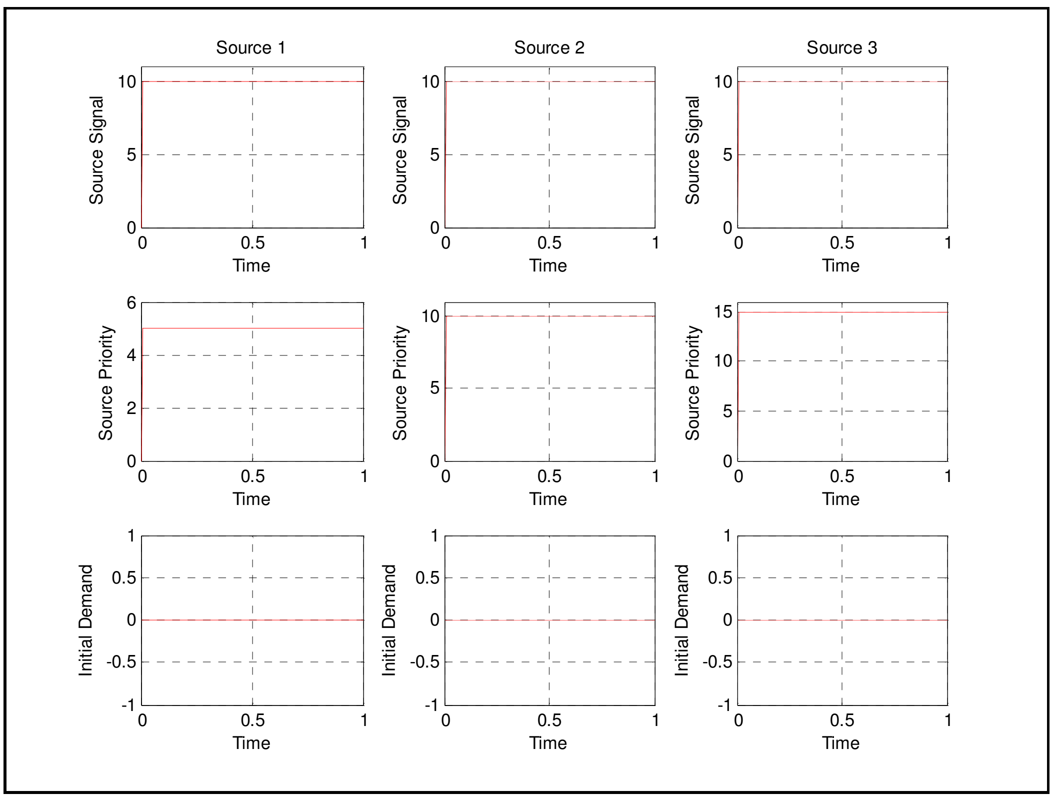

Fig 5.8: Inputs to the circuit - Example 2 - Sources only

From figure 5.9, it is clear that all three sources were disconnected from the grid, as there was no load to be supplied. The supply priorities and assigned grid demand values of all three sources are minus 1, to show it has been disconnected. (For priority values and grid demand values, the value minus one is unique and is only used to signifying that a source or load has been disconnected / shed, as explained earlier. This priority and grid demand value was assigned to the sources, by the 'T'-components.)

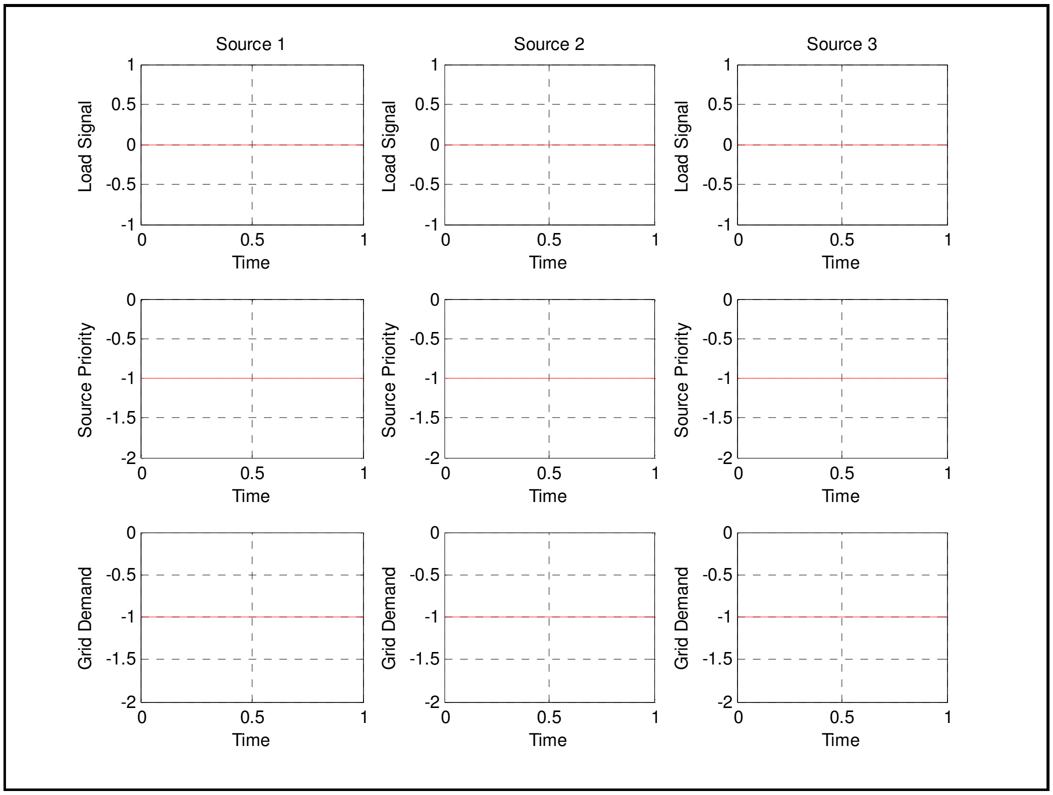

Fig 5.9: Outputs of the circuit - Example 2 - Sources only

5.4 Example 3 - Loads only

Similar to example 2, the same circuit is constructed but all the sources are replaced with loads. Consider figures 5.10 to 5.13.

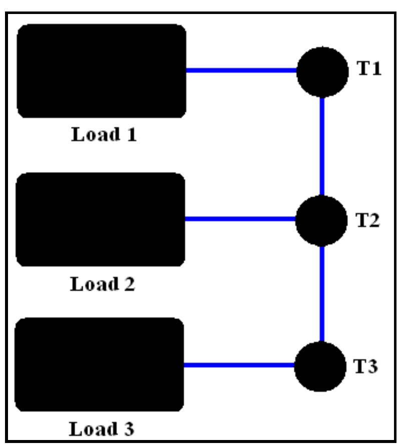

Fig 5.10: Simple representation of the circuit - Example 3 - Loads only

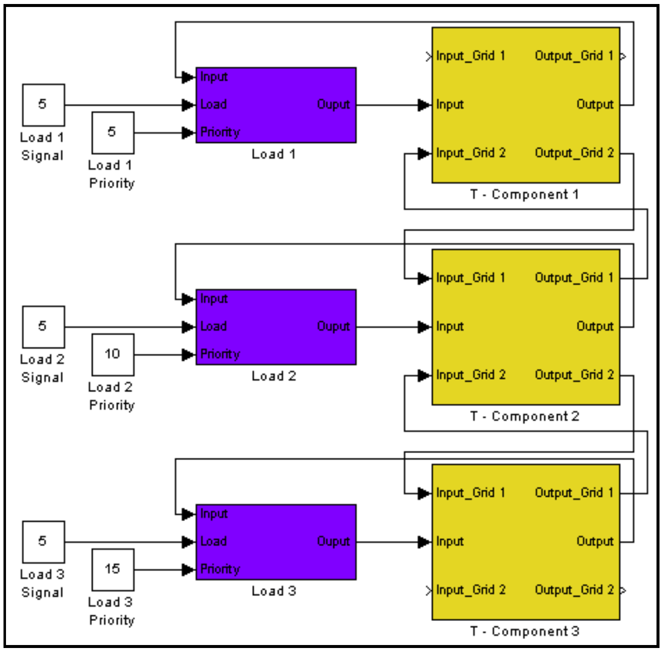

Fig 5.11: Simulink representation of the circuit - Example 3 - Loads only

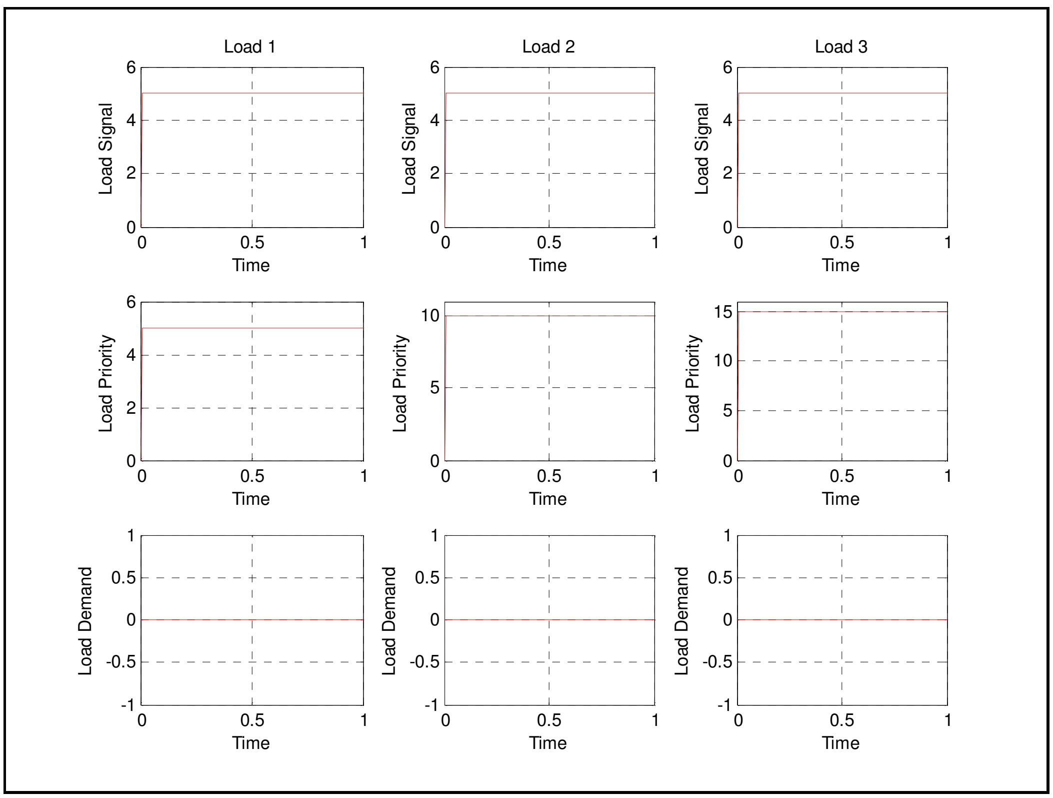

Fig 5.12: Inputs to the circuit - Example 3 - Loads only

In figure 5.12, the load request from all three loads is identical at 5 units of energy, and all at different priorities of 5, 10 and 15 respectively. Again, the demand of the loads communicated to the grid is zero.

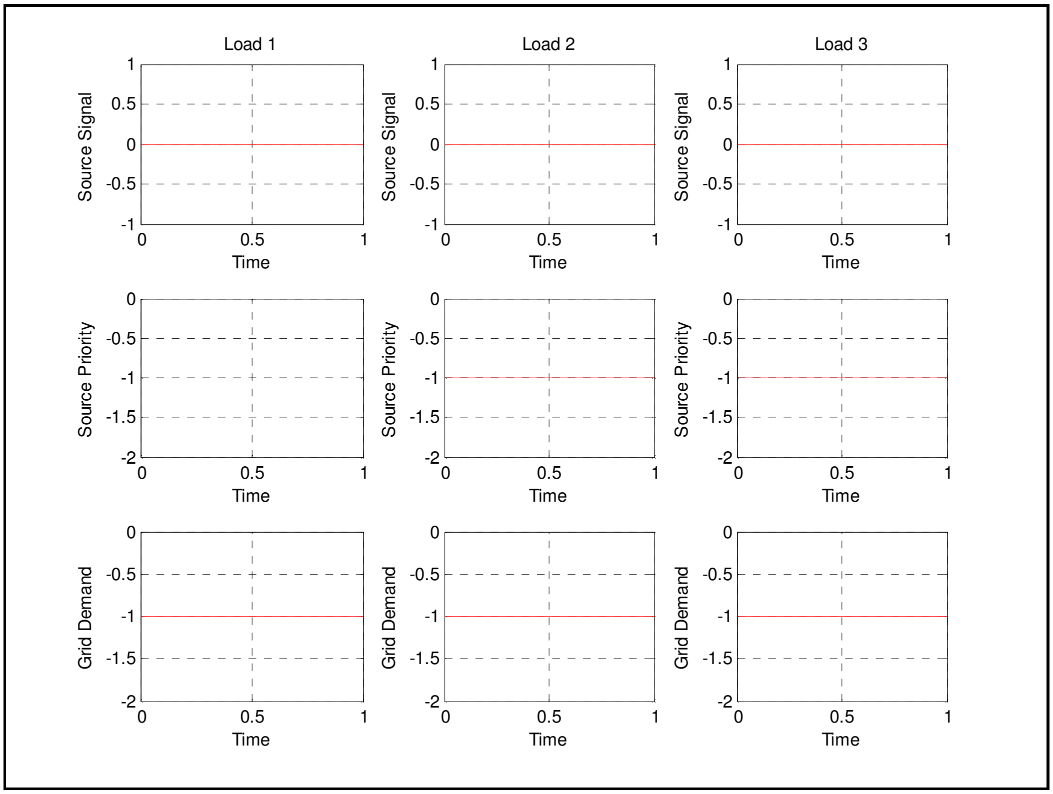

Fig 5.13: Outputs of the circuit - Example 3 - Loads only

From figure 5.13, it is indicated that all three loads were shed because there was no source present to supply it. Again, as mentioned in Example 2 – Source only, the priority and grid demand values for all three loads are assigned the unique value of minus 1, to signify that these loads have been shed, as explained earlier. (This priority and grid demand value was assigned to the loads, by the 'T'-components.)

5.5 EXAMPLE 4 - CHANGING SOURCE PRIORITIES

This example aims to show how a grid would solve itself when the Control-component (or traditional SCADA) changes the source priorities in a network. In addition, the initial demand of source 2 is set to 0.5 to explain the impact of this on the grid. (Note that the demand zones, as explained in Chapter 4, have been set to infinite in this example.) Consider figures 5.14 to 5.18.

From figure 5.16, it is indicated that all three sources have the ability to supply 10 units of energy throughout the 6 second simulation time. The load connected indicates that it requires 10, 20, and 30 units of energy for seconds 0 to 1, 1 to 2, and 2 to 3. For the period 3 to 6 seconds, it repeats this cycle.

Furthermore, the priority of source 1 remains constant at 5 for seconds 0 to 3 and then steps up to 15 for the remainder for the simulation. The inverse happens with source 3 which has a priority of 15 for seconds 0 to 3 and then decreases to 5 for the remainder of the simulation. Source 2's priority however remains constant at 10. (Assume that these changes in source priority were made by the Control-component.) The load's priority also remains constant at 5.

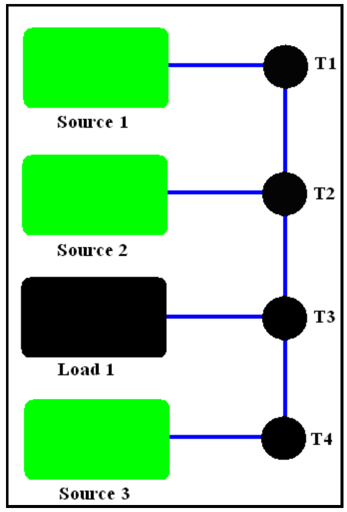

Fig 5.14: Simple representation of the circuit - Example 4 - Changing source priorities

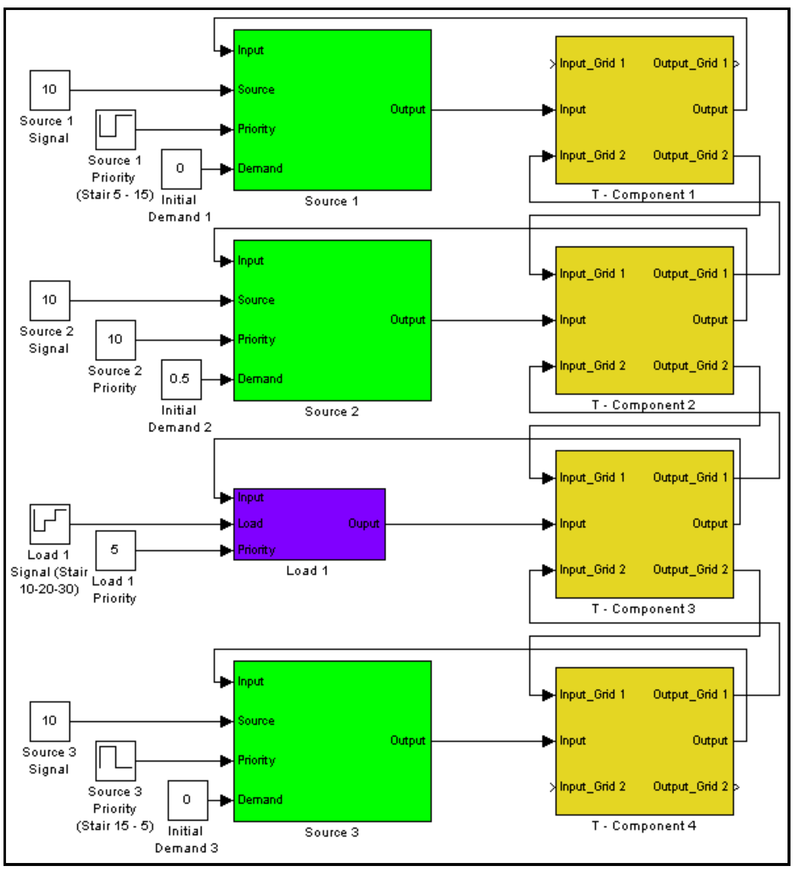

Fig 5.15: Simulink representation of the circuit - Example 4 - Changing source priorities

The initial demand for all the sources, except source 2 is 0. Source 2’s initial / internal demand is 0.5, which means that the owner of the source has other loads (auxiliaries or even island grids) already connected to the source, even before it connected to the grid. The demand for the load is zero.

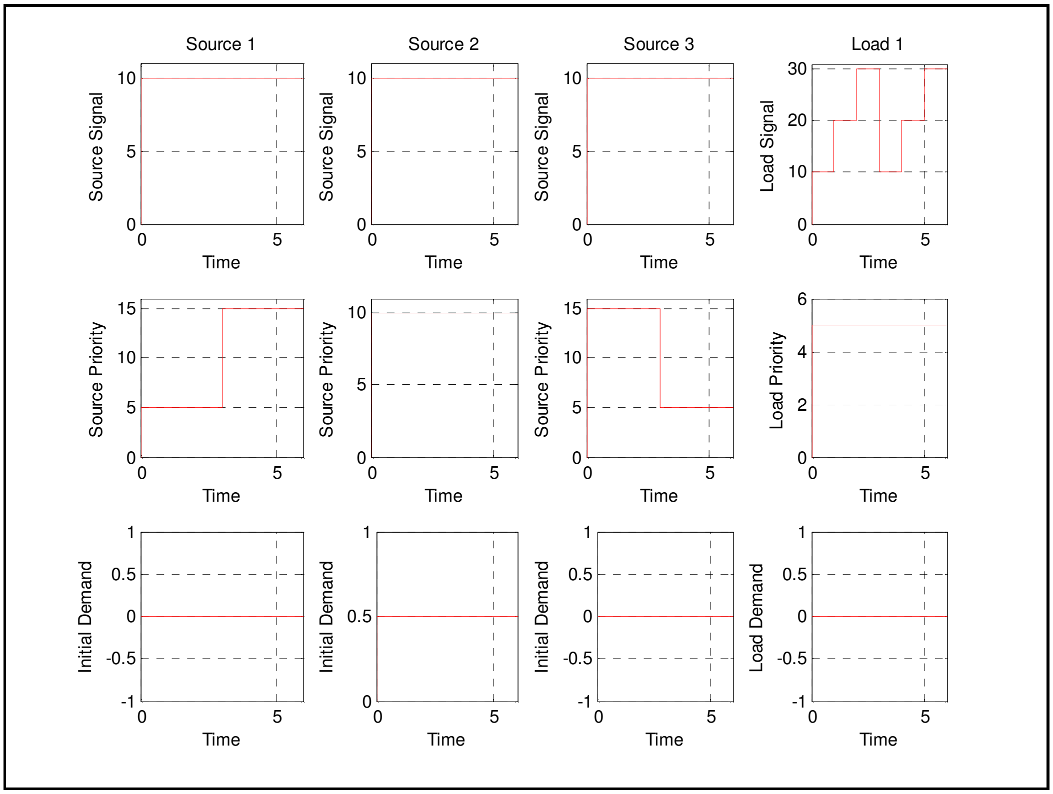

Fig 5.16: Inputs to the circuit - Example 4 - Changing source priorities

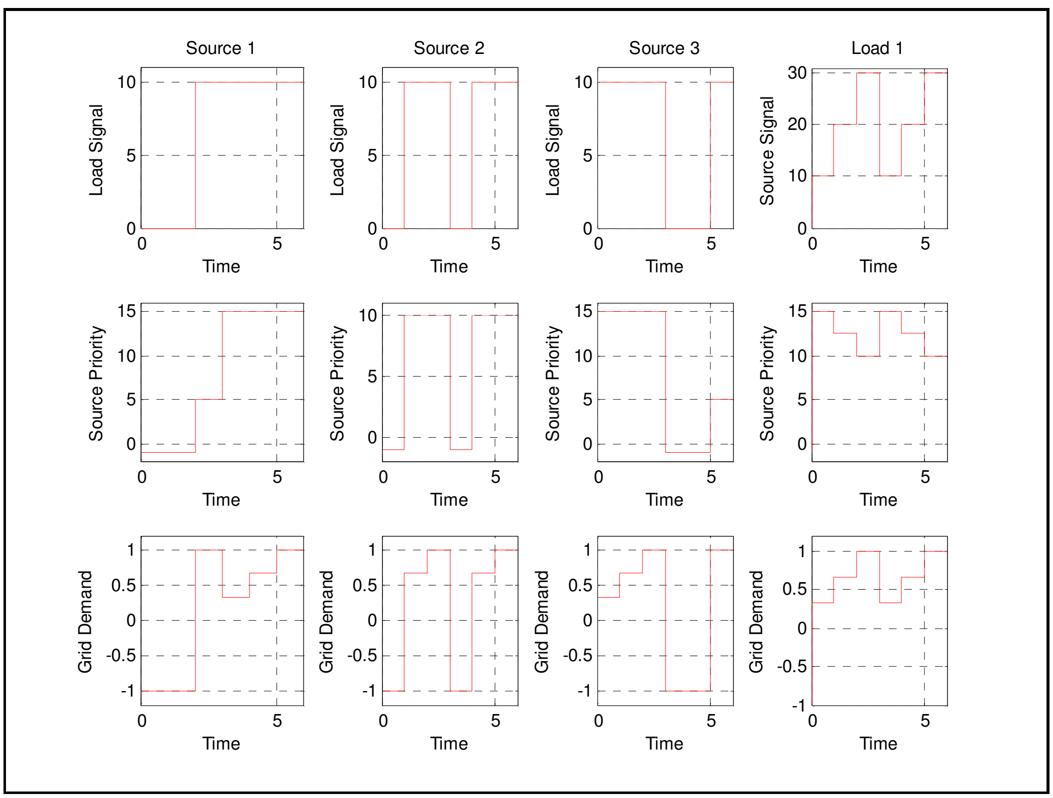

Fig 5.17: Outputs of the circuit - Example 4 - Changing source priorities

In figure 5.17, it is indicated at the top right that the load was supplied all its energy as requested. In seconds 0 to 1, source 3 had the highest priority and was able to completely supply the load. So source 1 and 2 supplied no energy and was consequently disconnected from the grid. Hence, their supply priority and grid demand values are '-1' to signify this. Source 3's supply priority of 15 matches that of what the load received, as it was the only source that supplied the load. The grid demand for this simulation period, as recognized by both the source and the load was the [Total load(s)/Total source(s)] = 10/30 = 0.33.

For seconds 1 to 2, the first source is still not used as the load can be supplied by sources 2 and 3. Hence, source 1's priority and demand remain '-1'. Both source 2 and 3 supply 10 units of energy to meet the loads request, and by combining their source priorities in a pro-rata manner, the supply priority of the load was [Source 2 supply / (Source 2 supply + Source 3 supply) * Source 2 priority + Source 3 supply / (Source 2 supply + Source 3 supply) * Source 3 priority = 10 / 20 * 10 + 10 / 20 * 15 =] 12.5 as indicated on the right, last column. Finally the grid demand is 20/30 = 0.66 for sources 2 and 3 and the load, as shown in figure 5.17.

For seconds 2 to 3, all three sources are required to supply the load. Hence, all the sources supply at their respective priorities the load which makes the supply priority to the load equal to 10 / 30 * 5 + 10 / 30 * 10 + 10 / 30 * 15 = 10. The demand for this period is 1 for all the loads and sources, as the load requirements are matched exactly to the available supply.

For the period 3 to 6 seconds, the load receives the same amount of energy, at the same supply priority and grid demand, as the first three seconds of the simulation. The only difference is that the supply priorities of source 1 and 3 was changed around, so that source 1 supplies throughout this period while source 3 only assist with supply in the last second. Because of this, the supply priorities and demand value of source 1 and 3 are also changed around while source 2 repeats the same pattern. (Consider the first and third column of figure 5.17)

This simulation is done to show how it is possible for the Control-component to change source priorities to either optimise the grid, relieve network constraints and in this case, one could assume that source 3 that was closer to the load and experienced some emergency and that source 2 may not have been as reliable as source 1. Hence, the Control-component interchanged the source priorities to allow the 'T'-Smart grid to solve itself in a different manner.

As previously indicated, Source 2 had an initial / internal demand which was unknown to the grid. However, the true energy supplied or demand of the source is very important when considering planned maintenance and capacity upgrades. As can be seen for second 0 to 1 and second 3 to 4 of the simulation, the demand the source experienced was 0.5 (due to loads other than that connected to the grid), while no energy was supplied to the grid. Note that the 10 units of energy selected in the simulation is the amount of energy available *after* non-grid loads where subtracted. Hence, at any given time it could only offer the grid 10 units of energy, which it did for seconds 1 to 3 and 4 to 6. In these seconds, all its grid available energy was used and hence its internal demand increased to 1.

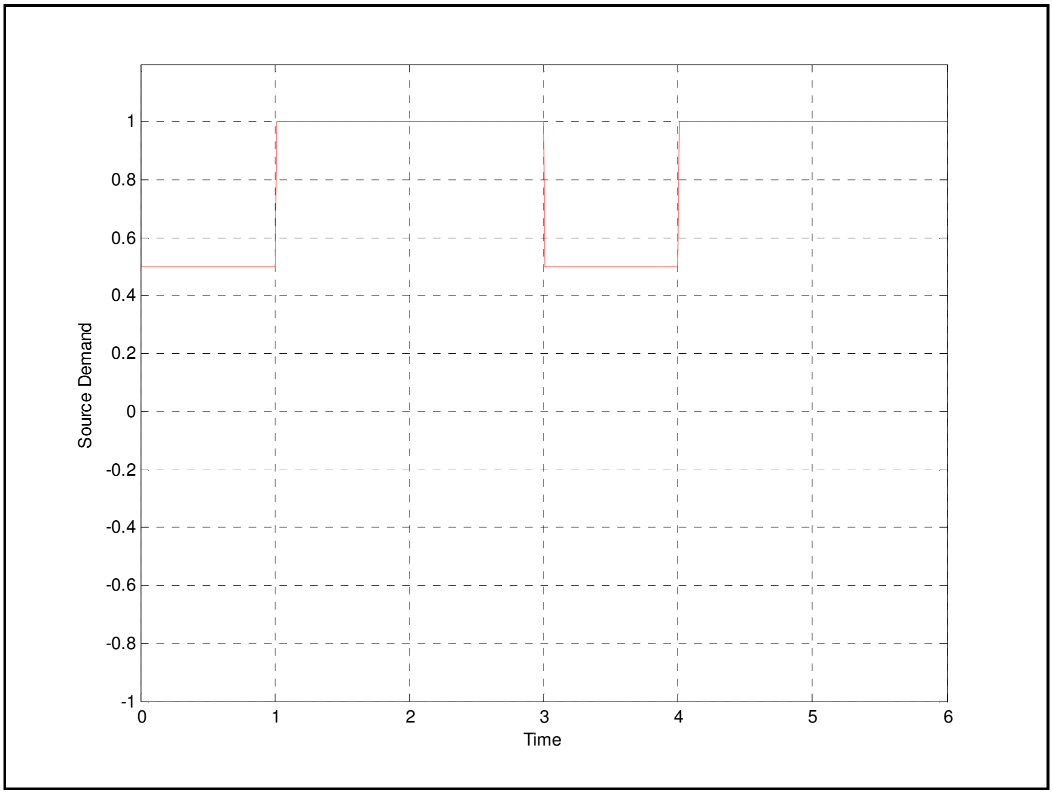

Fig 5.18: Outputs of the circuit - Demand of Source 2 - Example 4 - Changing source priorities

5.6 Example 5 – Sub-grids, Demand zones and Interventions

In this example, loads supplied from in-zone sources and out-of-zone sources are more clearly illustrated. In addition, the load shedding intervention is also simulated and explained. Consider figures 5.19 to 5.22.

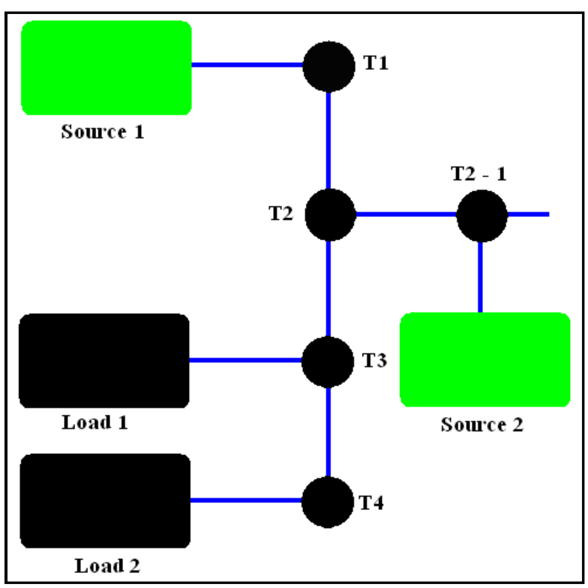

Fig 5.19: Simple representation of the circuit - Example 5 - Sub-grids, Demand zones and Interventions

In this grid configuration, there are four 'T'-components connected in a radial fed network where the second 'T'-component branches off into a sub-grid. In this sub-grid, there is only one source. (Hence, one can also assume that an entire sub-grid, which is assumed to always have spare capacity available, in this example, was reduced into a single resultant source connected to a second sub-network 'T'-component.)

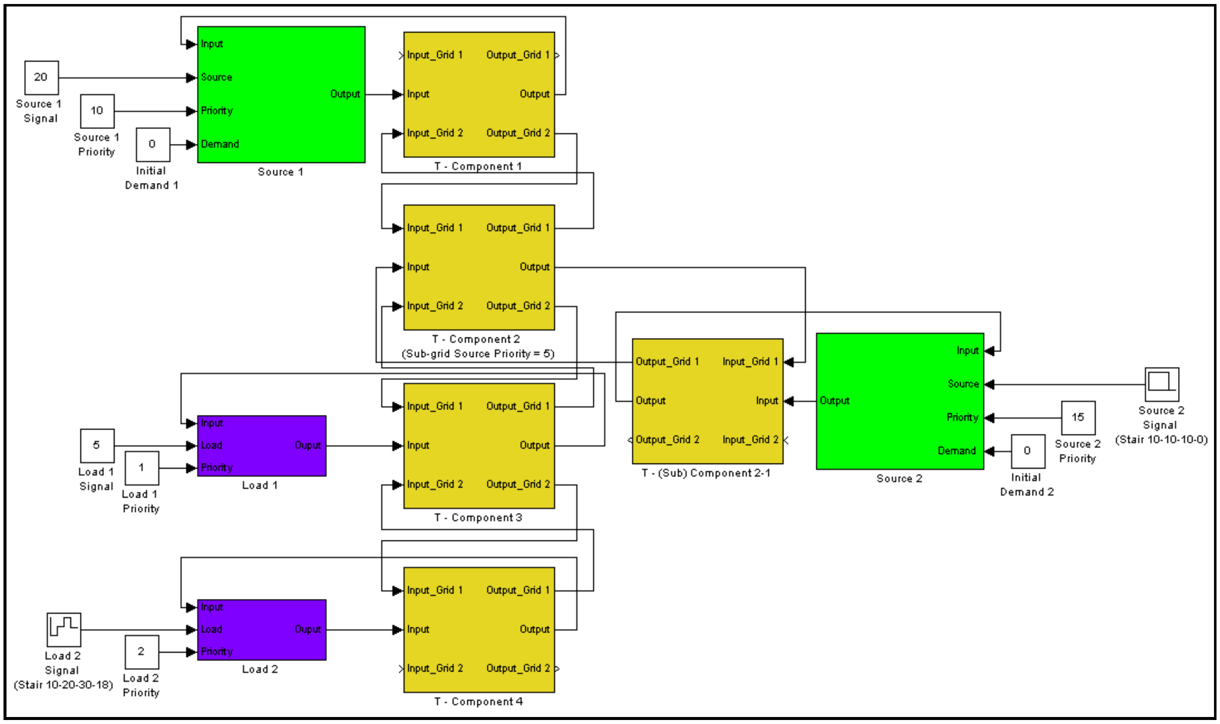

Fig 5.20: Simulink representation of the circuit - Example 5 - Sub-grids, Demand zones and Interventions

As seen in figure 5.21, Source 1 has 20 units energy available at a priority of 10 while source 2 (in the sub-grid) only has 10 units of energy available in the first three seconds after which it has no supply available in the final second. (Note however from figure 5.20; once the entire sub-grid of T2 is reduced to a single source or load, then it is assigned a new equivalent 'load' or 'source' priority value. In this case, as seen on T2 [Second 'T'-component], the new source priority as solved by the main-grid, considers the sub-grid's source as a priority 5 and not 15 [original value], which is a higher priority than the source in the main-grid. (Assume this control measure has been set by the Control-component to limit energy flow from a specific network due to cost, contingency (emergency) analysis or other considerations.)

The first load requests 5 units of energy for the entire 4 seconds of the simulation. The second load requests, 10, 20, 30, and 18 units of energy respectively for the four seconds of the simulation.

Further note, all the 'T'-components have been set to consider a source within two 'T'-component above or below it to be 'in-zone' and everything else as 'out-of-zone'.

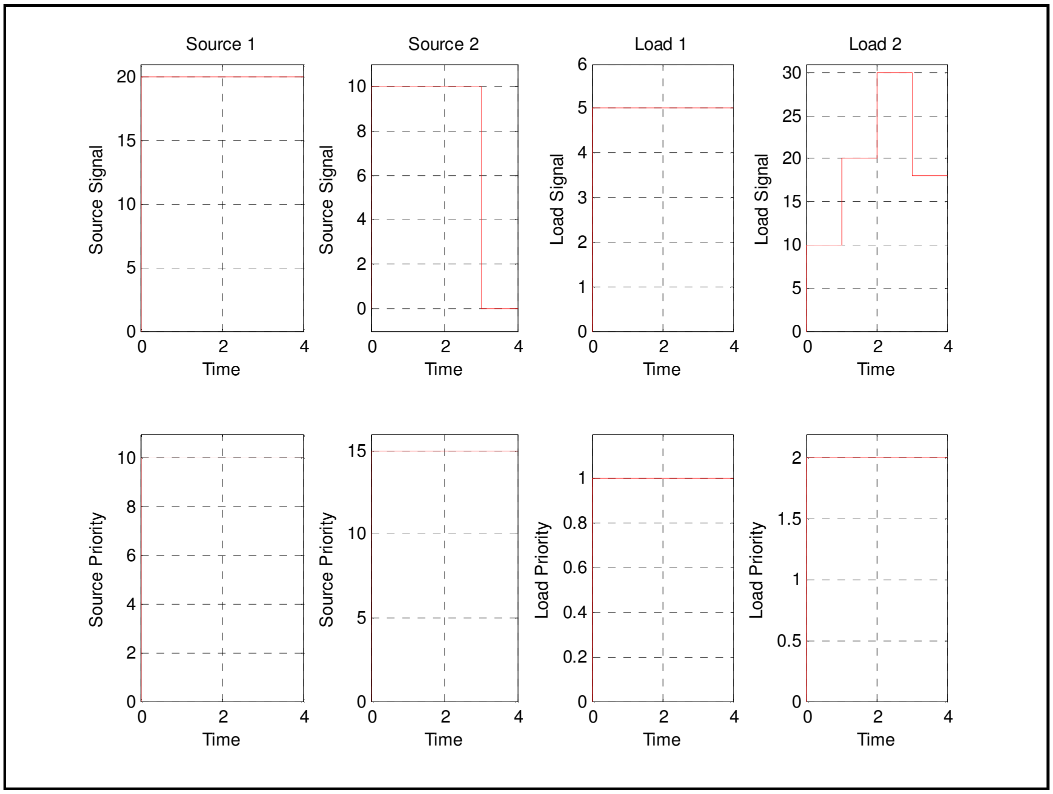

Fig 5.21: Inputs to the circuit - Example 5 - Sub-grids, Demand zones and Interventions

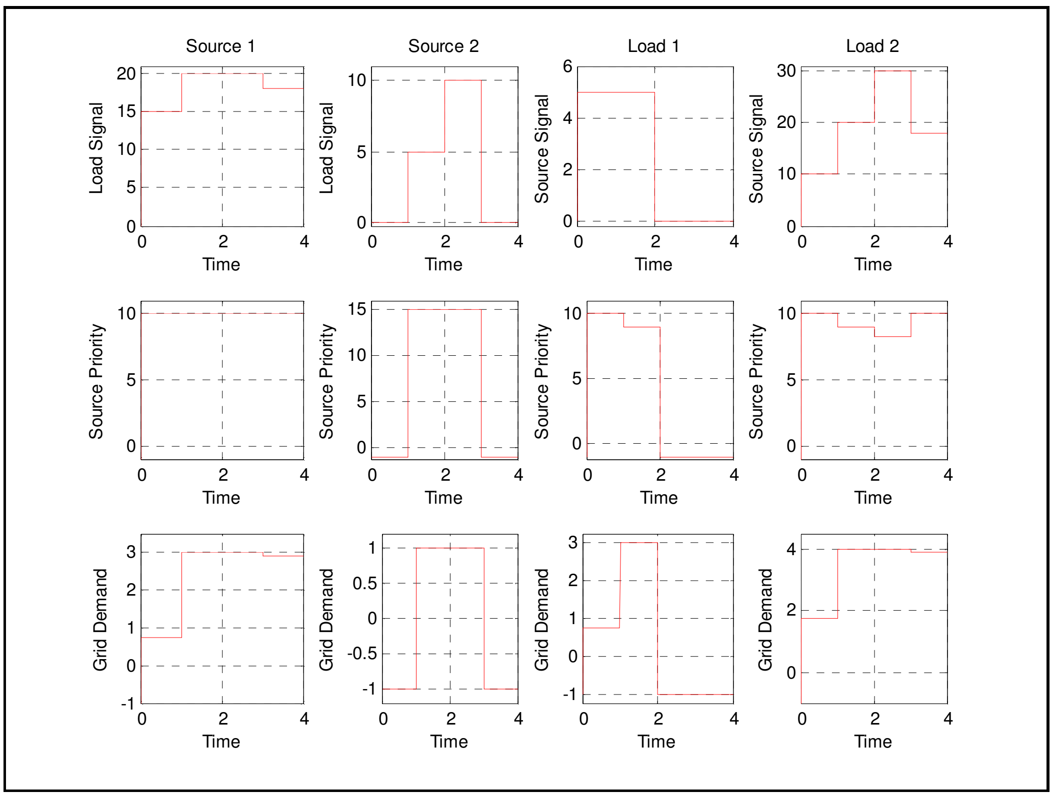

Fig 5.22: Outputs of the circuit - Example 5 - Sub-grids, Demand zones and Interventions

In the first simulation second, source 1 supplies the two loads with their respective demand requests as can be seen from the top row. Although source 2 has a higher priority, it was assigned a new equivalent source priority (by the second T component) when the sub-grid was reduced (to a single source) to be solved, as indicated earlier. Hence, according to the main-grid, the priority of source 2 was 5. Also, as can be seen from the supplied priorities of the two loads, it received the energy of the first source at a priority of 10. As for the demand, it is calculated at 15 units of energy supplied to all the loads, divided by the total energy available, hence; 15 / 20 = 0.75.

Note the energy source in the sub-grid is not taken into account in the main (first) grid's demand calculation. The reason for this is that energy from external grids may only be used when the local energy is insufficient. Hence, the local network is used first before the network towards a distant source is upgraded to import energy. This then limits the need to strengthen main networks but also forces customers to use the type of energy (priority) available in their area.)

In addition, note that the demand of load 2 was incremented by a factor of one to indicate that its source of energy was 'out-of-zone' as indicated earlier. The reason for this is that source 1 is more than two 'T'-components away from it. (Note that this function can be switched off by the Control- component, but if the Grid-operators want to charge for the exact network use to transport energy to the load, then this functionality can be used.)

In the second simulation second, the total load to be supplied by the main-grid was 25 units of energy (to both loads) which meant 5 units of energy needed be imported from the sub-grid. Hence, the supply priority to the loads was 20 / 25 * 10 + 5 / 25 * 5 = 9. (The sources kept their respective priorities as explained earlier.)

Because the demand in the main-grid was calculated based on only the loads and sources in that grid, the demand was 1. However, as indicated in Chapter 4, when an intervention occurs such as supply from an external grid, the demand value is incremented by two. Hence, source 1 and load 1 recognised this intervention and has a demand of 3. However, load two was out-of-zone as well, so it was incremented by another factor of 1 to result in a value of 4. Finally, the source in the sub-grid only recognised a demand of one, and this value is not incremented as there is no network problem in the sub-grid. (Hence, the main-grid's demand does not trigger demand zone and intervention costs in the sub-grid, as explained in Chapter 4, as this would not be fair to the sub-grid.) Note, also as indicated in Chapter 4, sources are only notified of grid interventions and not whether the loads are 'in-zone' or 'out-of-zone' as the SNCs are assigned to the loads.

For the third simulation second, load 2 (which has the higher priority) increases its energy requirement to 30 which is met by source 1 and 2, but results in load 1 being shed. Load 2 has a supply priority of 20 / 30 * 10 + 10 / 30 * 5 = 8.33. (The sources again remain constant with their supply priorities.) The demand in the main-grid remains 1 so that source 1 recognises the external grid supply intervention and indicates a value of 3 while load 2, which is 'out-of' -zone' and receives power from an external grid remains at 4. Source 2's demand remains 1 as it is part of a sub-grid and load 1 indicates a value of '-1' as it has been shed. (Note that load shedding is also considered an intervention, however, the demand value is not incremented again.)

In the final simulation second (seconds 3 to 4), load 2 reduces its request to 18 units of energy. This request can be met by the local source 1. However, source 2 cannot supply energy as seen in figure 5.21. Hence, source 1 is the only supply available and it cannot supply both load 1 and load 2. Thus, load 1 is shed and this is also considered an intervention.

So both source 2 and load 1 has priority and demand values of '-1' because the load was shed and the source does not have any energy available. The supply priority of load 2 was 10, which is equal to source 1 which supplied it. Finally, the demand value is 18 / 20 = 0.9. However, source 1 is aware than an intervention occurred so its demand is 0.9 + 2 = 2.9 while load 2 was 'out-of-zone' as well. Thus, its supply priority was 0.9 + 2 + 1 = 3.9.

5.7 EXAMPLE 6 – INCREASED DEMAND DUE TO INFRASTRUCTURE CONSTRAINTS

This example aims to demonstrate how the 'T'-Smart grid would react to grid infrastructure limitations and how this will affect demand inside this grid as well. Consider figures 5.23 to 5.26.

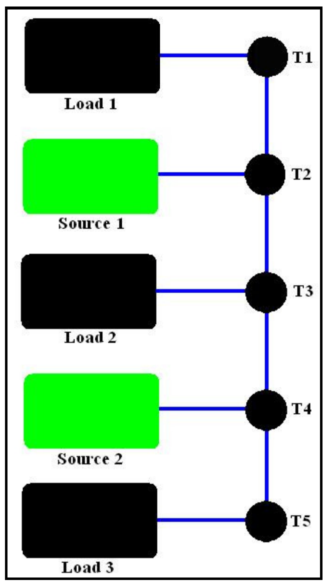

Fig 5.23: Simple representation of the circuit - Example 6 - Increased demand due to infrastructure constraints

The grid configuration comprises of a radially fed network with two sources and three loads. All the demand zones of all the 'T'-components are set to two 'T'-components above and below, and T3 (the third 'T'-component) has a FCL grid limit of 20 units of energy (Port 1) and the T4 (the fourth 'T'-component) has a Grid-component FCL limit of 7.5 units of energy (Port 3). (Consider Appendix A for more information.) Hence, at no time can more than 20 units of energy pass through T3's busbar and T4 cannot allow more than 7.5 units of energy to enter the grid.

As seen from figure 5.25, source 1 and source 2 has the capacity to supply the grid with 30 units and 20 units of energy, at a priority of 15 and 10 respectively. Load 1 and load 2 both request 2.5 units of energy at a load priority of 1 and 2. Finally, Load 3 requests 10 units of energy for the first simulation second and then 20 units for the remainder at a load priority of 3.

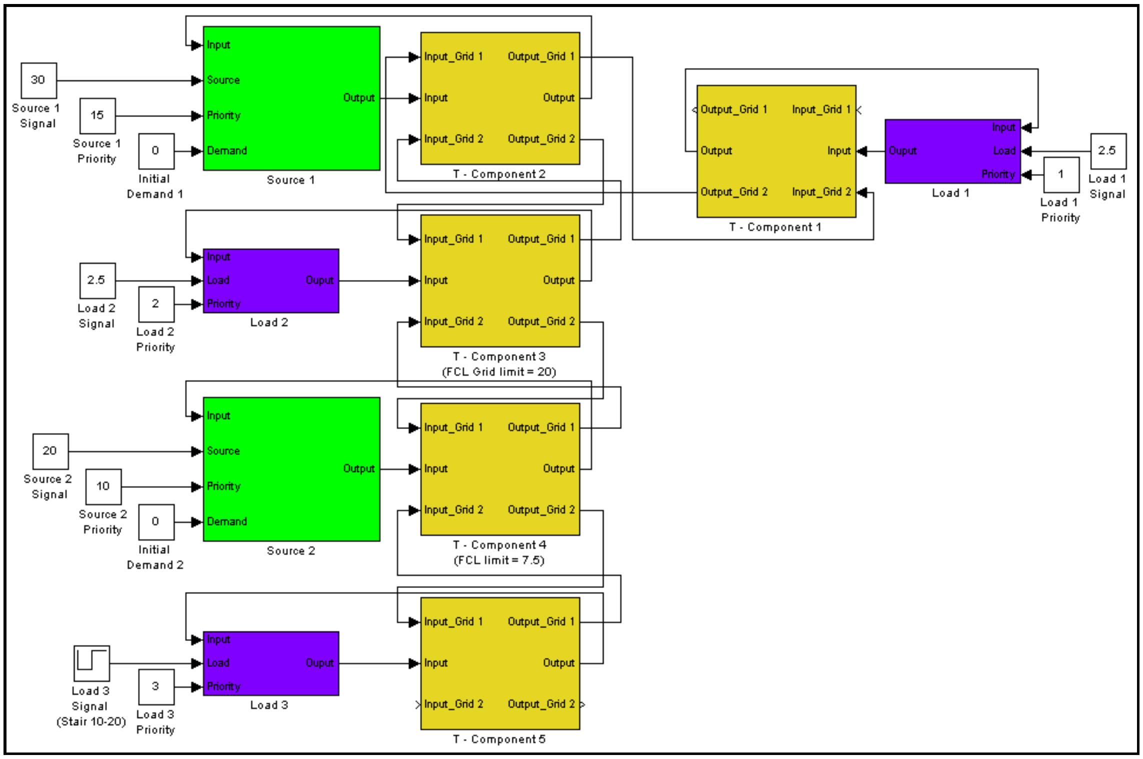

Fig 5.24: Simulink representation of the circuit - Example 6 - Increased demand due to infrastructure constraints

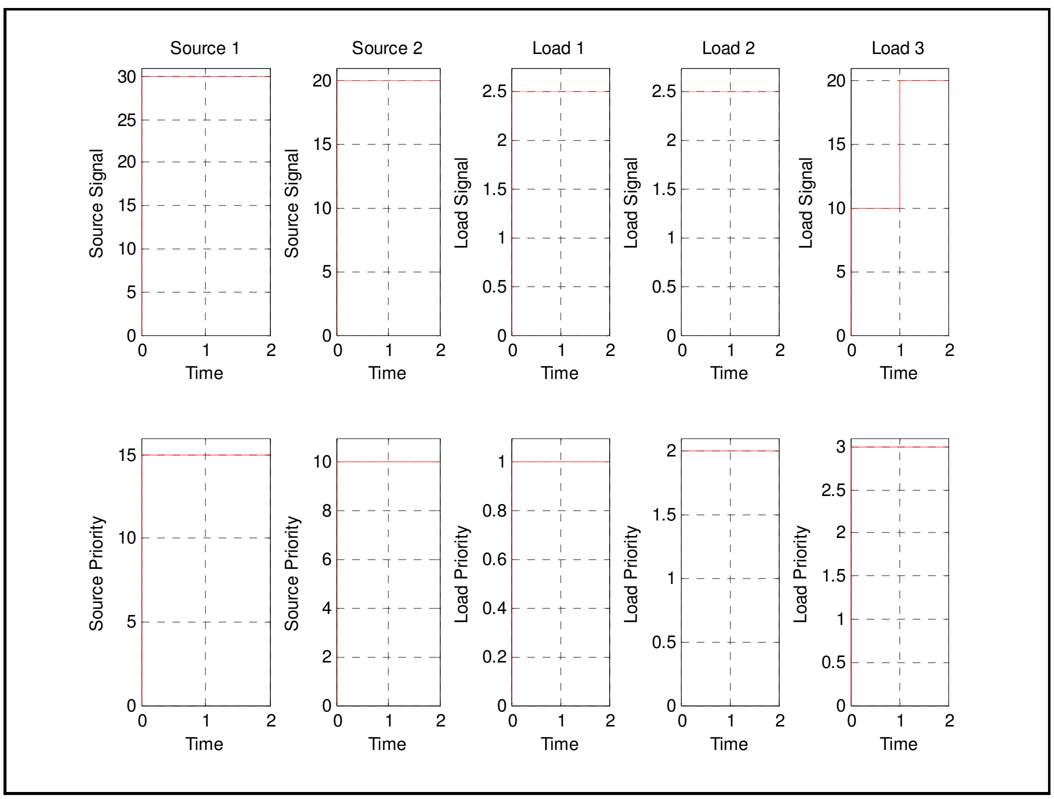

Fig 5.25: Inputs to the circuit - Example 6 - Increased demand due to infrastructure constraints

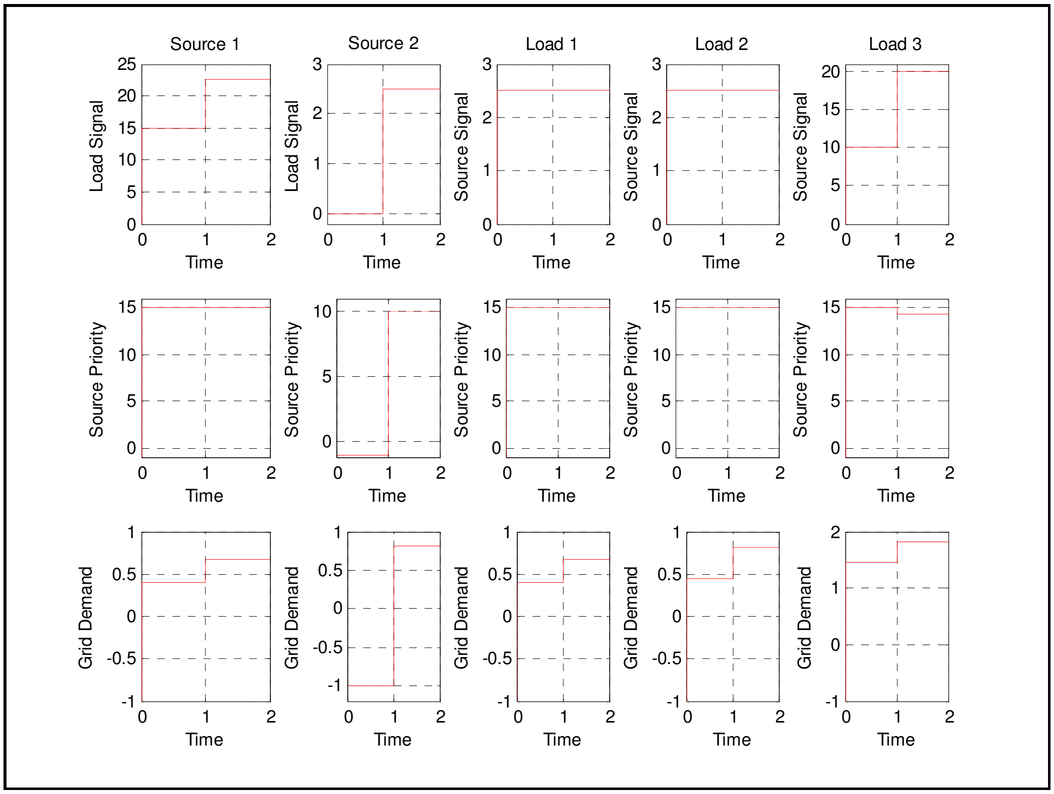

Fig 5.26: Outputs of the circuit - Example 6 - Increased demand due to infrastructure constraints

For the first simulated second, the entire load of the grid is supplied by source 1 (which has the higher priority of the two), as seen in the top row of figure 5.26. Hence, source 1's priority is shown on the graphs of the second row.

Now, recall that T4's FCL could only allow 7.5 units of energy into the grid. Hence, because of this, the entire source 2 is reduces to an equivalent source with only 7.5 units of available energy. Also, there is a busbar limitation at T3, which effectively 'splits' the demand calculations of the grid. So, for the side where source 1 and load 1 is connected, the demand is [total load (which is the maximum load that can pass through T3)] / [total source] = [10 + 2.5 + 2.5] / [30 + 7.5] = 0.4. However, because of the busbar limitation at T3, at best, Source 1 can only supply up to 20 units (of 30) to load 2 and load 3. Hence, because of this grid infrastructure limitation, the demand at the bottom side of the grid is [total load (on the side with the network constraint - because in this grid the supply source is above the limitation point)] / [total source (that can pass through T3)] = [10 + 2.5] / [20 + 7.5] = 0.455. (I.e. If the FCL is letting 20 units of energy through, it cannot also allow the load requirements of load 1 through as well, at the same time. Consider Appendix A for more information.) In addition, because the demand zones where only set to two units above and below, the supply for load 3 is 'out-zone' and hence the recorded demand is 1 + 0.455 = 1.455. (There is no grid demand value for source 2 as it didn't supply any energy to the grid.)

For the second simulation second, load 3 increases its demand request to 20 units of energy. Under normal conditions, the total load of the grid (2.5 + 2.5 + 20 = 25) could be supplied by source 1 alone, however, the limitation of the busbar of T3 has now necessitated the need for source 2 to assist in supplying the load (on the bottom side of T3). Hence, because source 1 can only supply 20 units of energy through T3's busbar, source 2 had to contribute 2.5 units of energy at the bottom side of the grid, in order to supply the load as seen in figure 5.26.

Furthermore, the bottom two 'T'-components (T4 & T5) is an equivalent circuits comprising of a source (of 2.5 units of energy available) and a load (20 units of energy required). Thus, at the interface with T3 (from T4's side), this equivalent model still holds as none of these parameters (or difference) have exceeded 20 units of energy. However, after load 2 connected to T3 it added another 2.5 units of required energy, and it comes to an equivalent model of 22.5 units of requested energy and 2.5 units of available energy. Because of T3's busbar limitation, at the interface of T2, this equivalent model gets reduced to load of 17.5 units of required energy alone. This, then means that source 1 and load 1 experiences a grid demand of [total load (including that of the equivalent reduced circuit values representing T3 to T5)] / [total source (only at top side of grid)] = [2.5 + 17.5] / [30] = 0.667. (Consider Appendix A for more information.)

Conversely, source 1 can only supply a maximum of 20 units of energy at the interface of T2 with T3 (due to T3's busbar limitation). The load connected to T3 only reduces the available energy so there is no second calculation of the reduced equivalent model for the circuit connected from T4 to T5. Hence, the demand for the components from T3 to T5 (load 2, source 2 and load 3) is calculated as [total load (from T3 to T5)] / [total source (from the equivalent grid of T1 and T2, plus source 2)] = [2.5 + 20] / [20 + 7.5] = 0.818. However, load 3's demand is incremented by 1 as it is 'out-zone' load. (Consider Appendix A for more information.)

As for the supply priority, as can be seen from figure 5.26, source 1 supplies load 1 and load 2, but due to the busbar limitation of T3, the energy supplied to load 3 was a combination of source 1 and source 2's energy. From figure 5.25, source 2 supplied 2.4 units of energy at a supply priority of 10 and source 1 supplied the remainder (17.5 units of energy) at a priority of 15. Hence, load 3's supply priority was 2.5 / 20 * 10 + 17.5 / 20 * 15 = 14.375.

5.8 Example 7 – Dividing energy in a constrained network

This example is similar to the previous, but shows how it is still possible to split energy flow in two separate directions, while still adhering to the limit of a constrained component in the grid infrastructure. Consider figures 5.27 to 5.30.

This grid comprises of a radially fed network with one source and two loads, where the loads are fed from either side of the busbar, which is supplied by the source. All the demand zones of all the 'T'-components are set to two 'T'-components above and below, and T2 (the second 'T'-component) has a FCL grid limit of 20 units of energy (Port 1). Hence, at no time can more than 20 units of energy pass through T2's busbar. (Consider Appendix A for more information.)

Throughout the simulation, Source 1 has the capacity to supply 40 units of energy at a priority of 15. The first load requests 20 units of energy for the first simulation second and 30 units of energy for the second simulation second. The second load requests 20 units of energy for the first simulation second and 10 units of energy for the second simulation second. The second load also has a lower priority than that of the first load.

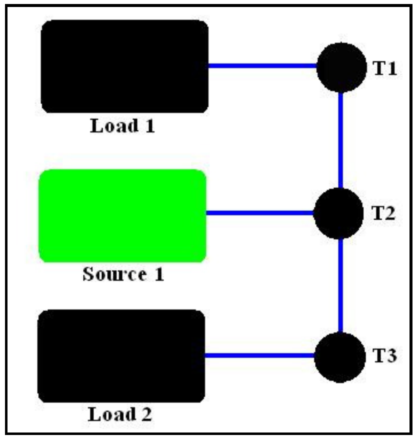

Fig 5.27: Simple representation of the circuit - Example 7 - Dividing energy in a constrained network

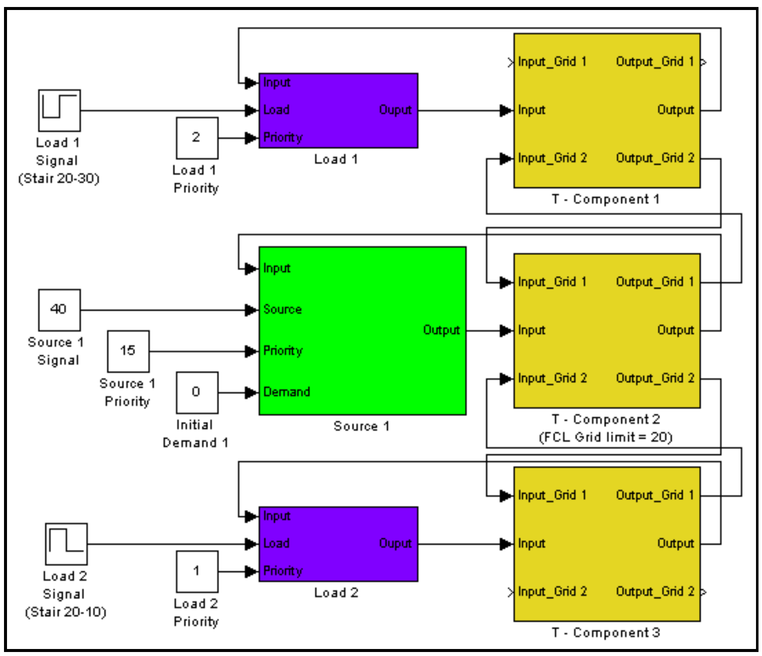

Fig 5.28: Simulink representation of the circuit - Example 7 - Dividing energy in a constrained network

As seen from figure 5.30, Load 1 and Load 2 are supplied with energy for the first simulation second from source 1 (The only source). Hence, the 40 units of energy from the source splits in two directions (above and below) and so supplies the loads without exceeding the limit rating of the busbar, which is 20 units of energy. (Note, there was no limit on the internal FCL [Port 3] which supplies the grid with the energy, only the busbar was limited. In addition, note that if the grid was configured in any other way, apart from the source being in the middle of the two loads, then the lowest priority load would have been shed and hence the solved state would be different.)

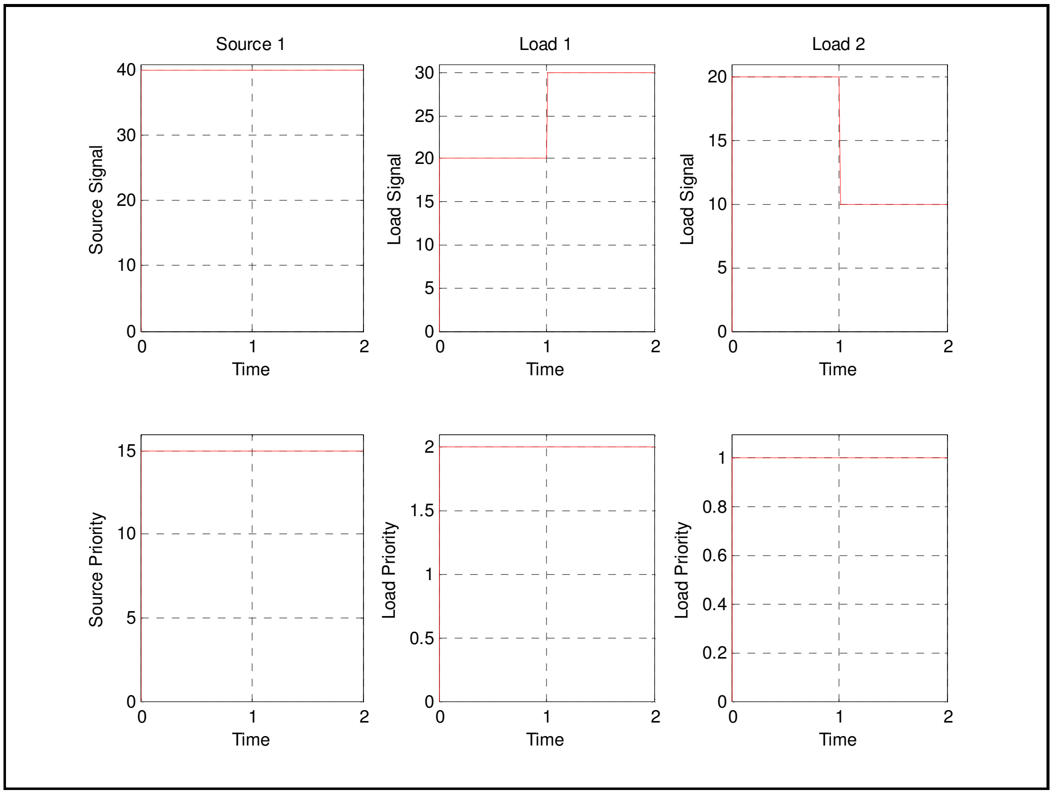

Fig 5.29: Inputs to the circuit - Example 7 - Dividing energy in a constrained network

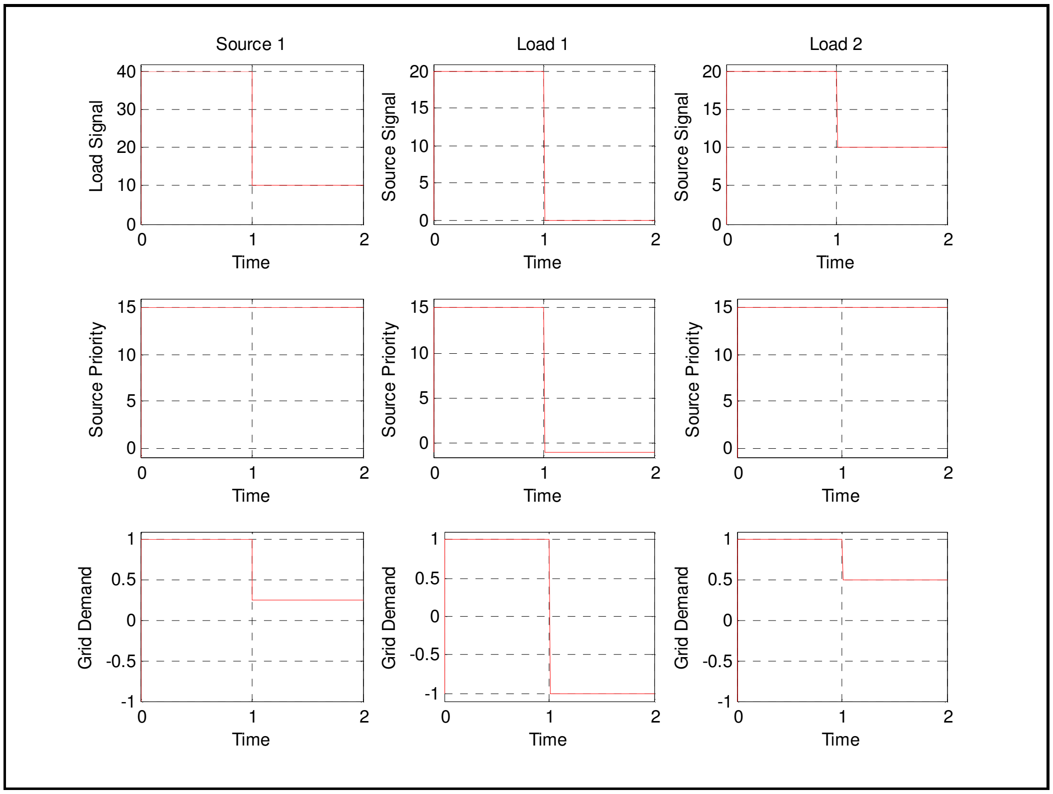

Fig 5.30: Outputs of the circuit - Example 7 - Dividing energy in a constrained network

For this first simulation second the demand in the grid is equal to (20 [Load 1] + 20 [Load 2]) / 40 [Source 1] = 1. Hence, this is the demand of source 1. However, for Load 1 and Load 2, because of the limitation of the busbar, both perceive source 1 as only being able to supply 20 units of energy to their respective branches of the grid. Thus their demand is calculated as 20 [Load 1 or Load 2] / 20 [Source 1 (taking into consideration the busbar limit)] = 1, as indicated. Finally, both Loads are supplied by the one source; hence all the supply priorities are 15 as seen in figures 5.29 and 5.30.

For the second simulation second, Load 1 (which as the highest supply priority) increases its load request to 30 units of energy which is beyond the busbar limit of the second 'T'-component. Because of this, Load 1 is shed as it cannot be supplied. For Load 2 (which has a lower priority) there is now sufficient energy for it to be supplied, even before it reduces its load request to 10 units of energy. (Note: Load 1 is a higher priority load then that of load 2. Hence, Load 2 is disregarded and the grid attempts to supply load 1. However, after failing to supply Load 1, due to the busbar limitation, there is still sufficient energy to supply the lower priority load and grid adapts to this and supplies it rather than supplying no energy at all.)

Load 2 is supplied the requested 10 units of energy and the demand for source 1 is, 10 [Load 2] / 40 [Source 1] = 0.25 as seen in figure 5.30, for Source 1. However, Load 2 is aware of the busbar limitation and recognizes that only a maximum of 20 units of energy can be supplied to it. Hence, for Load 2, the demand is 10 [Load 2] / 20 [Source 1 (taking into consideration the busbar limit)] = 0.5. For Load 1, because it is shed, its demand is '-1'.

Finally, Source 1 which has a supply priority of 15, supplies Load 2 at the same priority and Load 1's supply priority is '-1' because it is shed.

5.9 Example 8 – Energy storage element's first mode of operation

This example illustrates one of three modes of operation in which an energy storage element can operate. The energy storage element in this example must store excess energy from the source, when the grid doesn't require it and release energy when there is a shortfall in the grid. (This is the energy storage Element's first mode of Operation.) Consider figures 5.31 to 5.37.

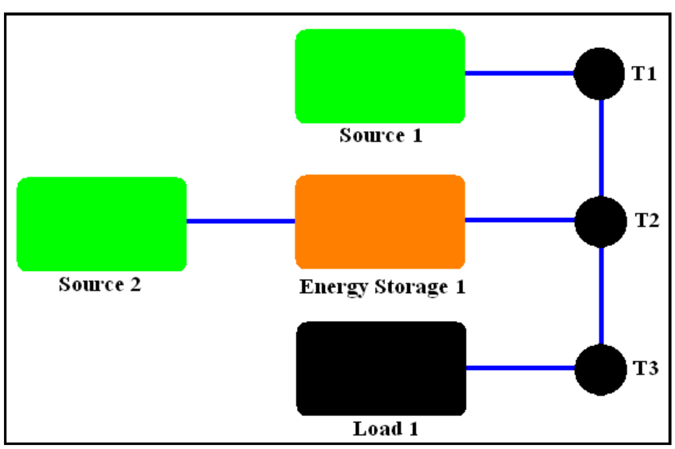

Fig 5.31: Simple representation of the circuit - Example 8 - Energy storage element's first mode of operation

The grid comprises of 'T'-components connected to a source, energy storage element and a load respectively. The energy storage element in turn is connected in series and between a second source and the grid. As can be seen from figure 5.32, the energy storage element is programmed with physical limitations such that it can only storage 1000 units of energy (saturation), its supply priority is 10 (although not relevant in this example, as explained later), its maximum discharge limit is 250 units of energy for a single simulation period / grid state period (0.01s) and its maximum charge limit is 30 units of energy for a single simulation period / grid state period (0.01s).

Its PLD is set at values 100 and 10, which means it would only discharge energy if it has been fully charged (to 100% of saturation) and if its internal stored energy level falls below 10%, then it would first charge up again (to 100%) before considering discharging. The demand zone of all 'T'-components in this example is set at 2 components above and below for the simulation. There are also no grid (infrastructure) limitations in this example.

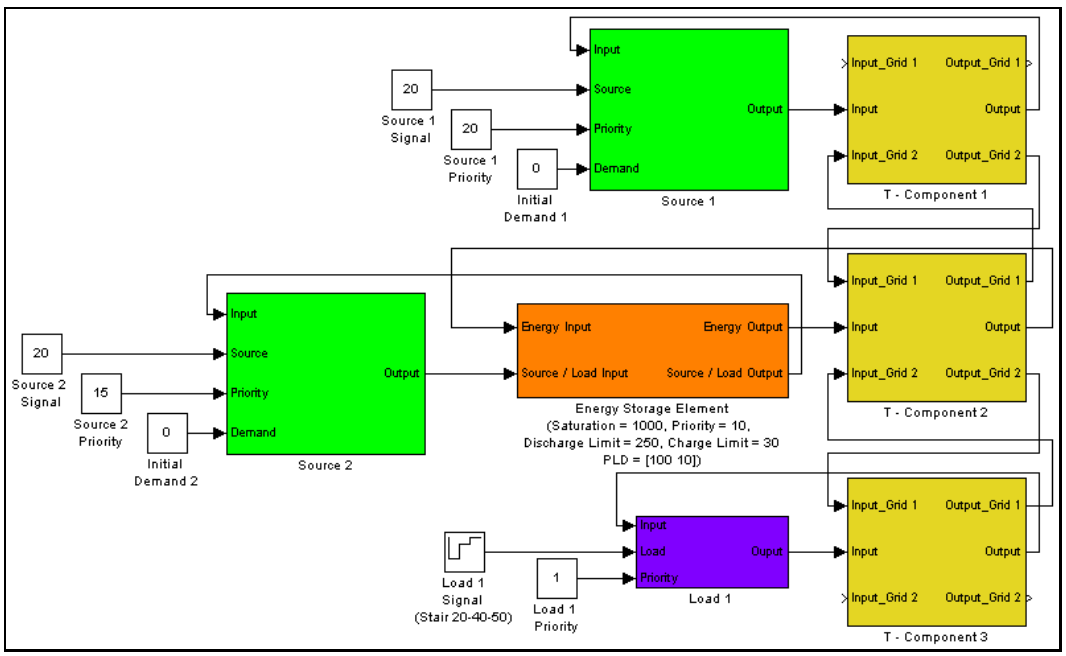

Fig 5.32: Simulink representation of the circuit - Example 8 - Energy storage element's first mode of operation

In this simulation Source 1 can supply 20 units of energy at a constant supply priority of 20. Source 2, which is connected to the energy storage element, can also deliver 20 units of energy at a constant supply priority of 15. Finally, Load 1 request 20 units, 40 units and 60 units of energy respectively over the three simulation seconds. The Load's priority stays constant at 1 for the entire simulation.

For the first simulation second, one would notice that some results change at approximately 0.5s. The reason for this is the effect of the energy storage element.

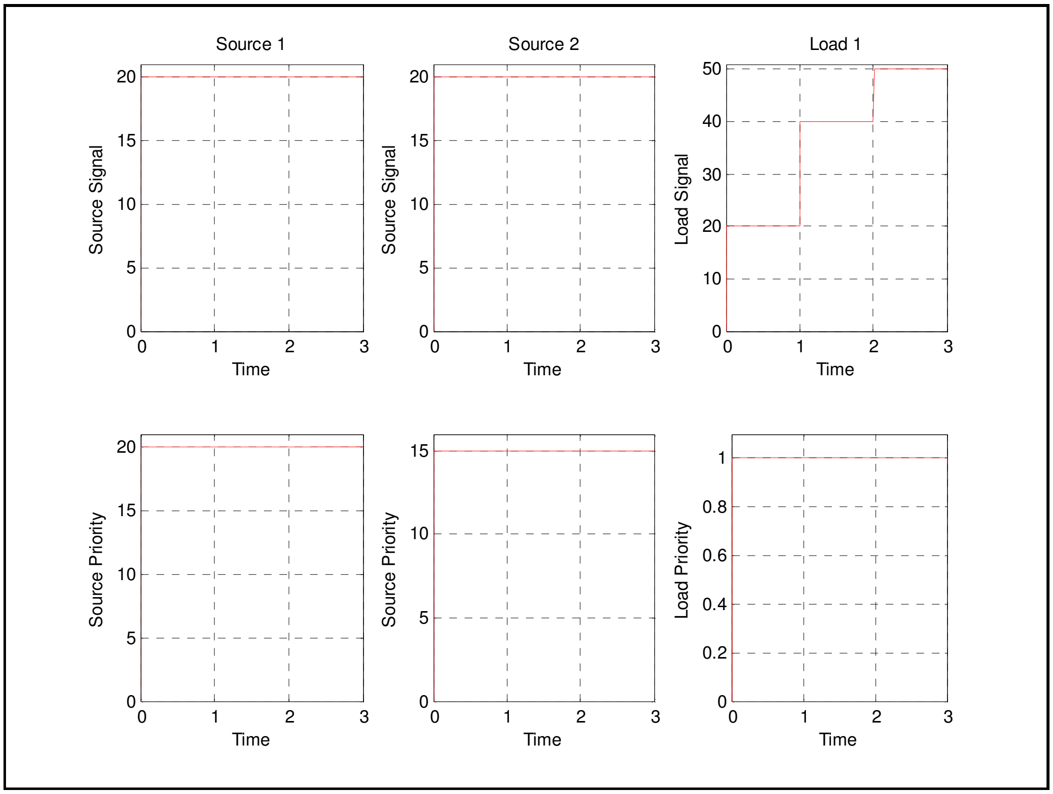

Fig 5.33: Inputs to the circuit - Example 8 - Energy storage element's first mode of operation

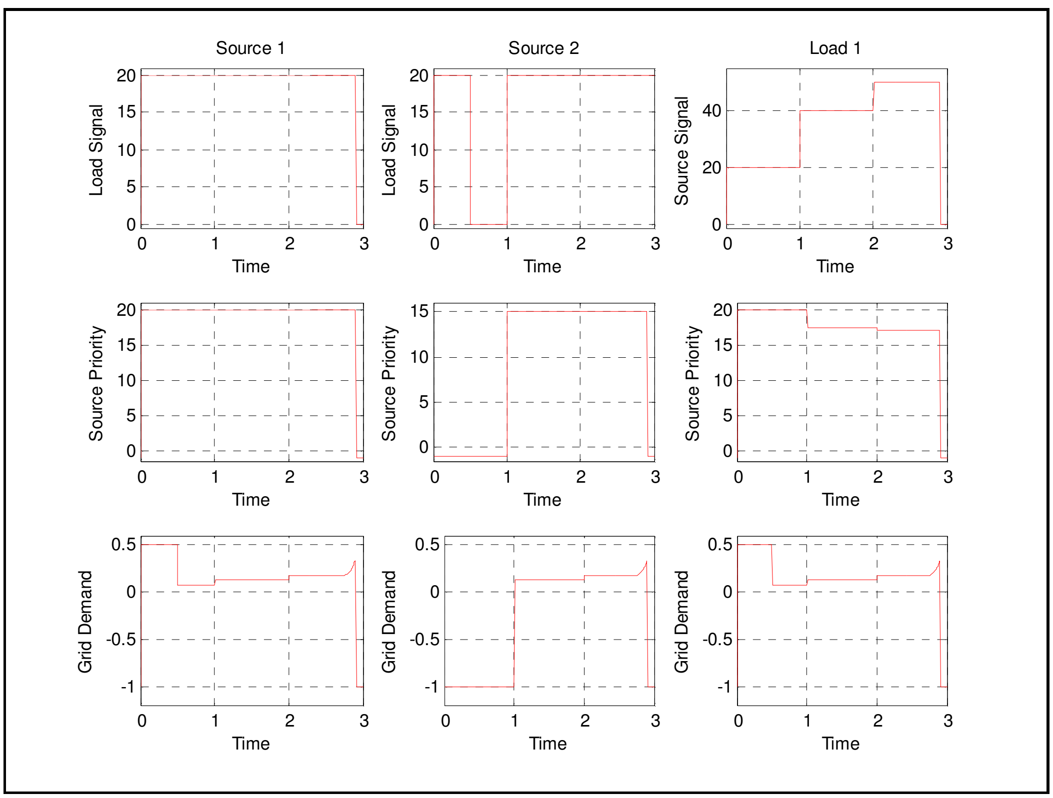

Fig 5.34: Outputs of the circuit - Example 8 - Energy storage element's first mode of operation

Initially, the energy storage element is fully discharged and there are two energy storage elements available to supply the load. Source 1 has a higher priority and hence supplies 20 units of energy, to the load, as requested by the load. So, in figure 5.34, source 1 supplies 20 units of energy for the entire first simulation second at a priority of 20 and load 1 receives 20 units of energy, in the same period, at a supply priority of 20. However, the grid demand for source 1 and load 1 changed at 0.5s. This is because it took 0.5 seconds for the energy storage element to charge up (to 100% of the saturation limit). Only once it has reached this charged energy level, will it start discharge, if required.

Hence, before 0.5 seconds, there were two energy sources and one load of 20, so the demand is 20 / (20 + 20) = 0.5. However, after 0.5 seconds the energy storage element was fully charged but its physical discharge rate limitation prevents it from being able to discharge all its stored energy at once. It can only discharge 250 units of energy for a given simulation period, so the demand is 20 / (20 + 20 + 250) = 0.069. (Note that as explained in the previous chapter, when energy is stored in an energy storage element, it does not impact on the demand, as this energy would have been lost if not stored.)

Also, as can be seen from figure 5.34, source 2 only supplied 20 units of energy for the first 0.5 seconds to the energy storage element, but in terms of the grid, its supply priority and demand is '-1' as it is 'disconnected' or not required by the grid. (Hence, one can assume that source 2 and the energy storage element is operating in an island mode during this simulation period.)

In the second simulation period one can see from the first column of figure 5.34, that both source 1 and source 2 had to supply their respective maximum available energy to meet load 1's request. Source 1 supplied at a priority of 20, source 2 at a priority of 15 and hence the load's supply priority was 20 / 40 * 20 + 20 / 40 * 15 = 17.5. The grid demand was seen by both sources and the load and calculated at 40 / (20 + 20 + 250) = 0.138. (Note that during this time, the energy storage element was only on standby as the sources' energy must be used first [because it is available].)

For the final and third simulation second, the load's request exceeds what the sources can offer and energy is required from the energy storage element. At 2.91 seconds, the previously stored energy runs out and the load is shed. This is shown in figure 5.34, for the load. During the time the load is supplied, the energy storage element takes on the supply priority of source 2. (Note that the unique priority value of the energy storage element is only considered when it interacts with the grid on its own, without a source or load connected to it, as explained in Chapter 4.) Hence, the load's supply priority is 20 / 50 * 20 (source 1) + 30 / 50 * 15 (source 2 + energy storage element) = 17.

Now, from figure 9.34, it is indicated that source 1 and source 2 (together with the energy storage element) supplied the load with its requested energy up to 2.91 seconds after which it disconnected or shed both the load and the sources for the remainder of the 0.09 seconds of the simulation. It is also indicated that the sources supplied energy at their respective supply priorities before being assigned the '-1' disconnected value after 2.91 seconds.

Finally, as can be seen from figure 5.34, the demand in the system is recorded the same for all the sources and the load. It is also noticed that at approximately 2.76 seconds, the demand increases with a sharp tail, before being assigned the '-1' value due to disconnect. The reason for this is that due to the energy storage element's physical limitation of only being able to supply a maximum of 250 units of energy in a single simulation period (0.01), the demand up to 2.76 seconds is 50/(20 + 20 + 250) = 0.1724.

However, after 2.76 seconds, the internal energy level of the storage element falls below this discharging level and due to the decrease in available energy, the calculated demand increases.

Hence, at every simulation interval of 0.01 seconds (after 2 seconds), the energy storage element's internal energy decreases by 10 units of energy. However, when it reaches 10% of its saturation value, it stops to discharge and starts charging again. (This was defined by the PLD = [100 10] parameter.) Hence, there are only 900 units of energy (Saturation minus10%) available to the grid and because the energy storage element supplies 10 units of energy every 0.01 seconds, the energy runs out in 900 / 10 * 0.01 = 0.9 seconds after 2 seconds. (The first discharge only took place at 2.01 seconds, resulting in the final run-out at 2.91 seconds.)

This then means that the demand, just before disconnection took place, was at the value just before 10% Saturation. This value is thus 1000 units of energy (Saturation) * 10% = 100 units of energy and the value just before this level was reached was 110 units of energy when calculating the discharging rate as explained earlier. Thus the grid's demand (peak tail) before shedding all sources and the load was 50 / (20 + 20 + 110) = 0.33.

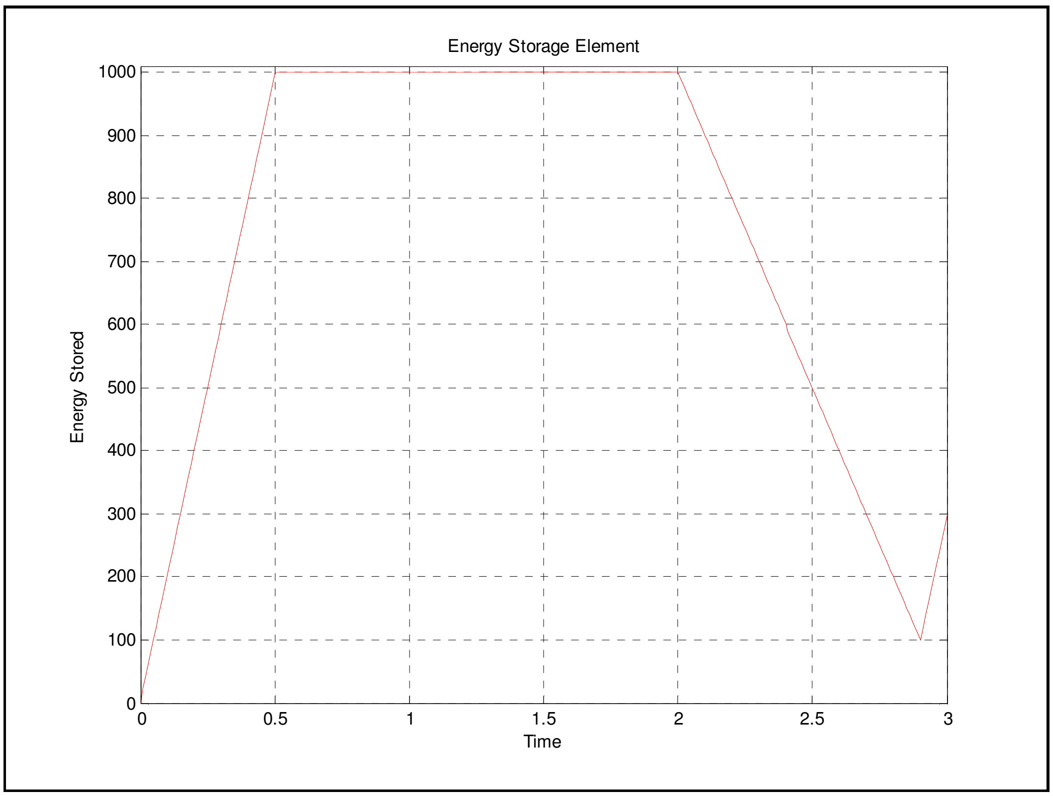

Fig 5.35: Outputs of the circuit - Energy level inside Energy storage element - Example 8 - Energy storage element's first mode of operation

What was explained earlier is depicted in figure 5.35. For the first 0.5 seconds, the energy storage elements charges and does not yet contribute to the demand calculation. From 0.5

seconds up to 2.91 seconds, it affects the demand calculation as it either has energy available or discharging in this period.

Also, as explained earlier, after 2.76 seconds, the energy level drops below the 250 discharge energy limit which is the maximum rate at which it can supply energy. Then, as this energy drops further to the 10% energy level (between 2.76 seconds and 2.91 seconds) each instance of reduced energy availability contributes to a higher grid demand.

Finally, at 2.91 seconds, the 10% Saturation load level is reached and the energy storage element denies supplying any more energy. Thus, because at that instance the load requirements exceed the source availability, all sources and the load are disconnected. Note however, that the energy storage element is charging energy for the final 0.09 seconds of the simulation from source 2. (In this mode of operation, it cannot store energy from source 1 as well. It can only do so when operated and connected on its own to the grid, as shown later. Hence, this mode of operation only benefits the owner of source 2.)

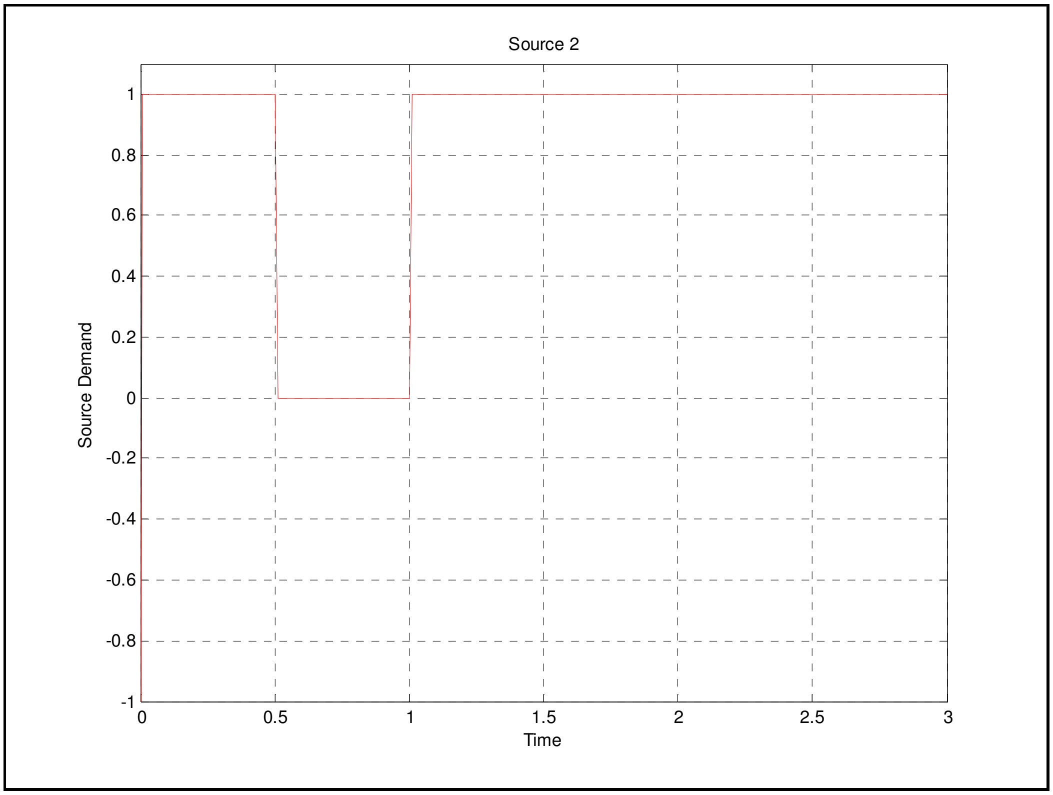

Fig 5.36: Outputs of the circuit - Demand of Source 2 - Example 8 - Energy storage element's first mode of operation

In addition, as seen in figure 5.36 (and figure 5.34), source 2 supplied the energy storage element with 20 units of energy (its maximum) for the first 0.5 seconds, before being disconnected from it. Between 1 and 2 seconds, it supplied 20 units energy to the load, together with source 1. Between 2 and 2.91 seconds it supplied 20 units of energy to the load together with source 1 and the energy storage element. After 2.91 seconds, it again supplied the energy storage element with 20 units of energy as is the case with the first 0.5 seconds.

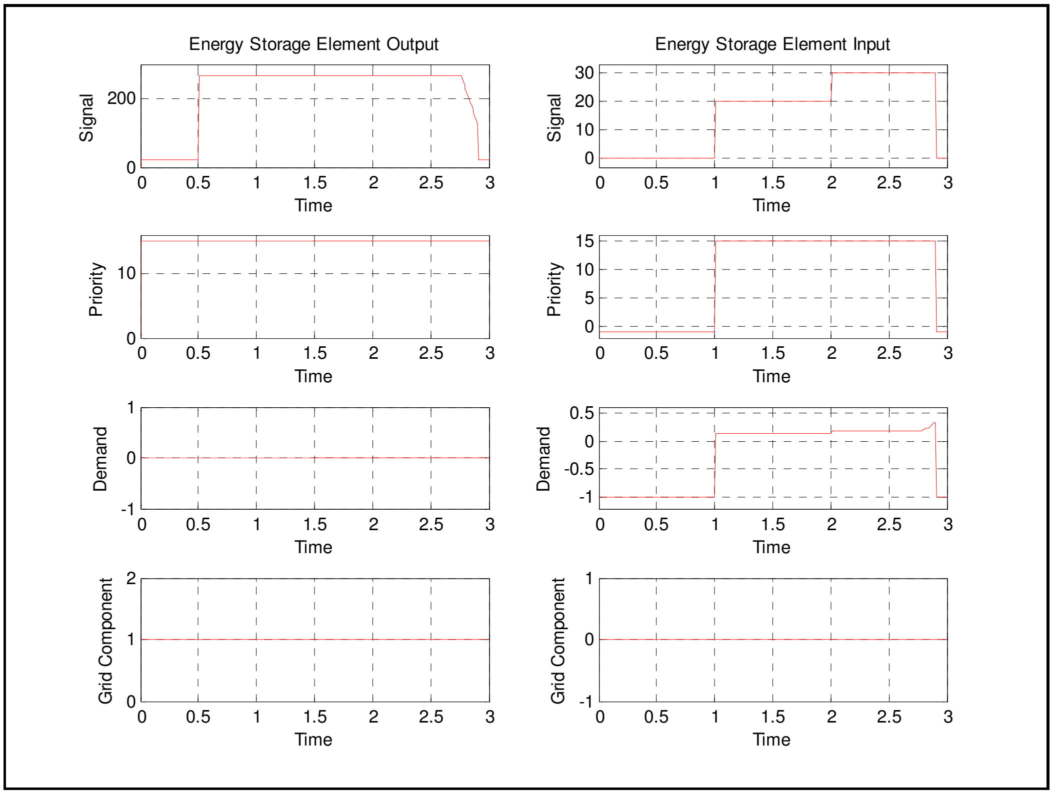

Fig 5.37: Outputs of the circuit - The Energy storage element's output to the grid and Input from the grid - Example 8 - Energy storage element's first mode of operation

As can be recalled from Chapter 4 and with further insight from Appendix A, the energy storage element can communicate in different ways with the grid. In this example it emulates a source. As can be seen in the first column of figure 5.37, for the first 0.5 seconds it emulates a source without energy (zero signal value during this period) and from then onwards it has 250 units of energy available up until 2.76 seconds.

Between 2.76 seconds and 2.91 seconds its energy level decreases so it emulates a source with decreasing energy. At 2.91 seconds, it stops discharging energy to the grid and emulates a zero energy source. Throughout the period, it has a supply priority of 15 (unlike what it is set to), because it acts as an extension to source 2 and hence emulates source 2's supply priority. The initial demand communicated to the grid is 0, which represents a source with no other load (not related to the grid but to the source itself) connected to it. And, because it emulates a source, its grid demand value is '1'. (Consider Appendix A for more information.)

The second column depicts what the grid requests from the energy storage element. For the first second, no energy is requested and hence the supply is zero, the priority and demand '-1' and the Grid-component value '0'. (The grid is now acting as a load, when it communicates with the energy storage element. Hence, the zero Grid-component value is used throughout the simulation. Consider Appendix A for more information.)

For the second simulation second, 20 units of energy is requested. The energy storage element decides not to use its internal stored energy but to simply conduct the energy of source 2 to the grid. It also does so at source 2's supply priority of 15 and the grid demand communicated to the energy storage element is 0.138, as calculated earlier.

For the final simulation second, the grid requests 30 units of energy until 2.91 seconds, when the energy storage element cannot discharge anymore energy. Hence, 20 units of energy from source 2 and 10 units of energy from the actual energy storage element are supplied to the grid (together with the supply from source 1 to supply the load). This is again supplied at a priority of 15 as the energy storage element takes on the priority of the source, in this mode of operation. The grid demand received is again exactly the same as calculated and explained earlier.

5.10 EXAMPLE 9 – ENERGY STORAGE ELEMENT'S SECOND MODE OF OPERATION

This example illustrates another of the three modes of operation in which an energy storage element can operate. The energy storage element in this example tries to predict the power consumption of the first load, in order to only request a constant load profile from the grid over time. Ideally, energy requirements from this load exceeding the constant energy request to the grid must be supplied from the stored energy element. Energy requirements from the load, less than the constant energy request to the grid, are used as an opportunity to store energy for future peak demands.

Although an artificial intelligent system was never developed to accomplish this, another logical system is substituted instead and is also used to highlight the effects of a possible shortfall in such a future developed system as explained in Chapter 4. (This is the energy storage Element's second mode of Operation.) Consider figures 5.38 to 5.43.

The grid comprises of 'T'-components connected to a source, energy storage element and a load respectively. The energy storage element in turn is connected in series and between a load and the grid. As can be seen from figure 5.39, the energy storage element is programmed with physical limitations such that it can only store 1000 units of energy (saturation), its supply priority is 10 (although not relevant in this example - explained later), its maximum discharge limit is 500 units of energy for a single simulation period / grid state period (0.01s) and its maximum charge limit is 30 units of energy for a single simulation period / grid state period (0.01s).

Its PLD is set at values 100 and 10, which means it would only discharge energy if it has been fully charged (to 100% of saturation) and if its internal stored energy level falls below 10%, then it would first charge up again (to 100%) before considering discharging. The demand zone of all 'T'-components in this example is set at 2 components above and below for the simulation. There are also no grid (infrastructure) limitations in this example.

In this simulation Source 1 can supply 25 units of energy at a constant supply priority of 20. Load 1, which is connected to the energy storage element requests 5, 10 and 20 units of energy respectively for each of the simulation seconds, at a load priority of 1. Finally, load 2 request 10 units of energy for the first 2.5 seconds, after which it increases its load request to 25 units of energy. This load's priority remains constant at 2. (Note that Load 2 has a higher priority than Load 1, which is connected to the energy storage element.)

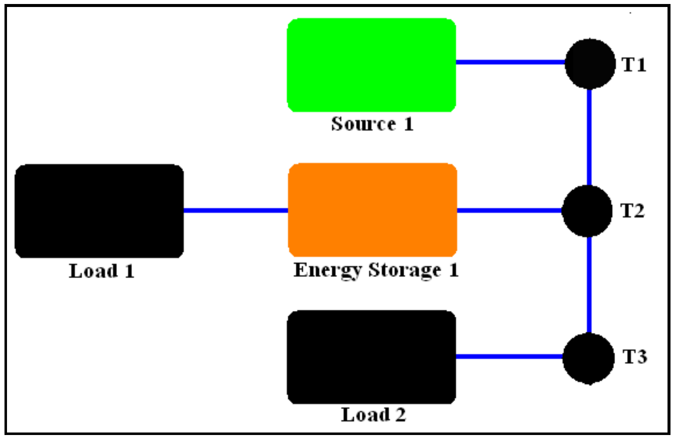

Fig 5.38: Simple representation of the circuit - Example 9 - Energy storage element's second mode of operation

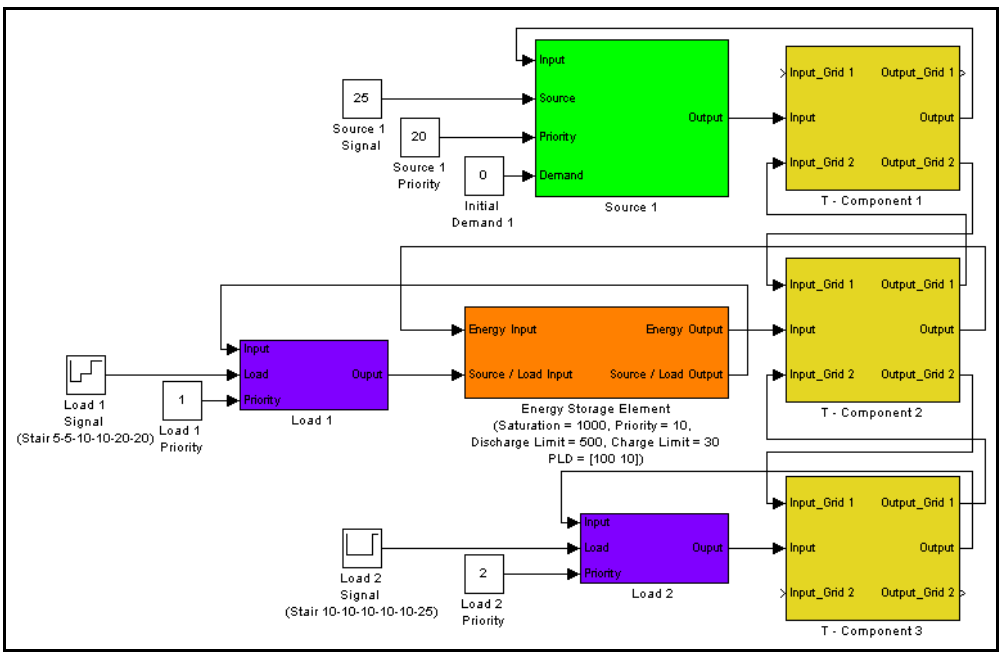

Fig 5.39: Simulink representation of the circuit - Example 9 - Energy storage element's second mode of operation

For the first simulation second, there is 25 units of energy available from source 1, of which 10 units of energy is used to supply the energy storage elements and 10 units of energy goes to Load 2. However, Load 1 only requested 5 units of energy during this period. Hence, it is supplied by 5 units of energy from the energy storage element while the remainder of 10 - 5 = 5 units of energy is used to start charging the empty energy storage element. (Note that a fixed charging rate of 10 units of energy is assumed, which is equal to 1% of the saturation limit.) The supply priority of Source 1 was 20, and one can see from figure 5.41, that Load 1 and Load 2 are supplied by this priority. Then, because the total of the load requested by the grid is 20 and source 1 can supply 25 units of energy, the demand during this simulation period is 20 / 25 = 0.8.

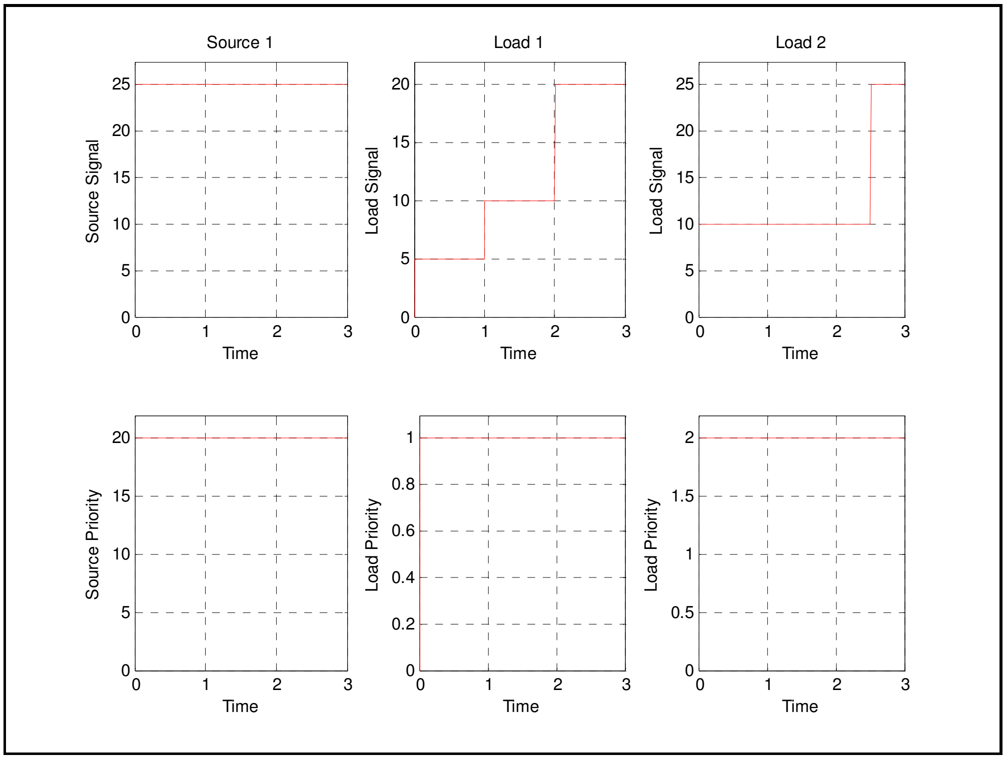

Fig 5.40: Inputs to the circuit - Example 9 - Energy storage element's second mode of operation

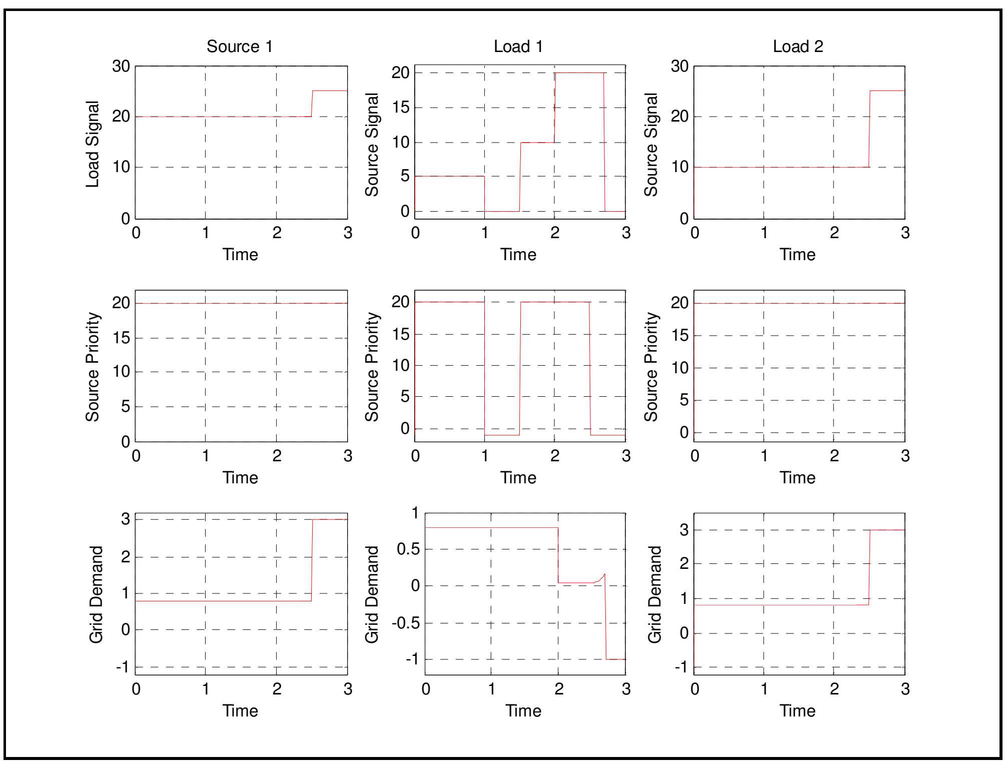

Fig 5.41: Outputs of the circuit - Example 9 - Energy storage element's second mode of operation

In the first half of the second simulation second, Load 1 requests exactly the same amount as what the energy storage element requests from the grid. Because it is busy storing energy (as it has not yet reached saturation) it cannot conduct energy, and thus sheds Load 1 to use all the energy to charge up. At 1.5 seconds, the energy storage element reaches its saturation and starts conducting energy to load 1 until the end of the second simulation period. Hence, the supply priority from 1s to 1.5s for load 1 was '-1' and from 1.5s to 2s was 20, which is equal to the supply priority of source 1. Load 2 has a supply priority of also 20, throughout the second simulation second (because it is supplied from source 1). Again, similar to the previous simulation period, the total load requested by the grid is 20 and source 1 can supply 25 units of energy, and hence the demand is 20 / 25 = 0.8.

For the third simulation second, Load 1's energy request exceeds the constant energy rate requested from the grid (by the energy storage element) of 10 units and it is then supplied by both the grid and the energy storage element.

However, at 2.5 seconds, Load 2 (which has a higher priority) increases its energy request from 10 units to 25 units. Thus, the grid sheds Load 1 and the energy storage element, because the energy storage element emulates the load priority value of Load 1, which is lower than that of Load 2. Thus, Source 1 only supplies Load 2, after 2.5 seconds. Load 1 is then only supplied by the remainder of the energy inside the energy storage element, which runs out at 2.7 seconds. Hence Load 1 is supplied until 2.7 seconds, at a priority of '-1' because it is shed during this period from the grid. (Hence, in this case the load is 'disconnected' from the grid and is assigned a '-1' priority value, even though it receives energy from the energy storage element.)

After this, for the remaining 0.3 seconds it is shed from the energy storage element which ran out of energy and it retains the '-1' supply priority value. Load 2 is supplied for the entire remainder of the simulation second at a supply priority of 20, by source 1.

The demand from 2s to 2.5s is equal for the source and the two loads at 20 / 25 = 0.8. After 2.5 seconds, load 1 (including the energy storage element) is shed from the grid and load 2 requests the total amount of energy from source 1 of 25 units and hence the demand is 1. However, because load 1 was shed, this value is increased by 2 and source 1 and load 2 have a grid demand values of 3 due to this intervention.

Load 1 however is supplied by the energy storage element in an island type operation and one can see that the demand value increased from 2.5s up to 2.7s, as the energy storage element is losing energy. It peaked at 2.7s at a demand of 20 / 120 = 0.1666. (20 Units of energy requested by load 1 and 120 units is left in the energy storage element before it reached the level at which it stops to supply energy and charges up again until full capacity because of the Percentage Level Discharge initial setting. Thus, even though it is disconnected from the grid, the load is still supplied with energy and it is communicated to the load that the emulated source's demand [energy storage element] is increasing which acts as an early warning for future load shedding.)

After 2.7s, the energy storage element goes back to charging mode; however it is still shed from the grid. Hence, load 1's priority and demand value is '-1' to show it is disconnected from the grid.

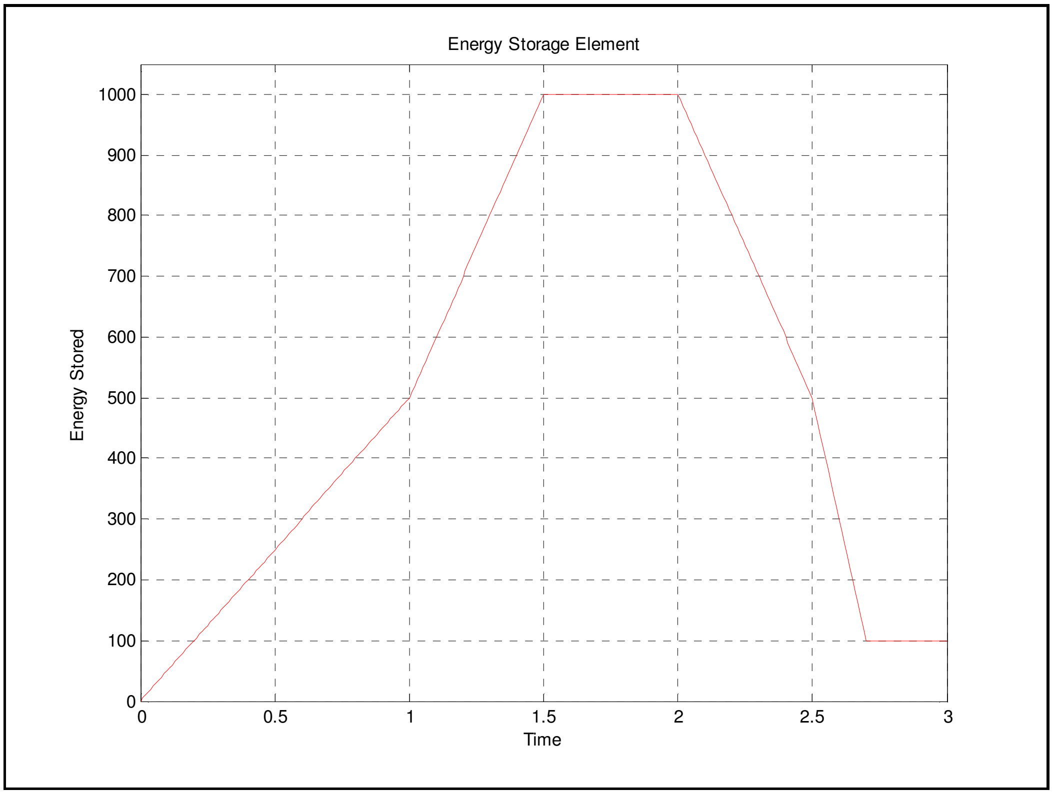

Fig 5.42: Outputs of the circuit - Energy level inside Energy storage element - Example 9 - Energy storage element's second mode of operation

In figure 5.42, it is shown how the energy storage element charges up the first simulation second at rate of 5 units of energy every 0.01s simulation / grid state period such that it reached 500 units of energy at 1s. After this from 1s to 1.5s, it charges up at a rate of 10 units of energy every 0.01 simulation / grid state period, because load 1 is shed. It then reached saturation at 1.5s and then does not discharge between 1.5s and 2s as explained earlier.

Between 2s an 2.5s, it discharges at a rate of 10 units of energy per 0.01s simulation / grid state period until 2.7s when load 2 increases its energy requirements leaving load 1 shed from the grid. Then, 20 units of energy per simulation / grid state period is supplied from the energy storage element until it reaches its set maximum discharge level and stops supplying load 1. For the remainder of 0.2 seconds, there is no energy available in the grid and it remains shed and not charging any energy.

As explained earlier, in this second mode of operation the energy storage element emulates a load which requests a constant amount of energy from the grid. This value is predefined at 1% of the saturation value. Its load priority communicated to the grid is '1' (same as load 1). Its internal demand is '0' and because it emulates a load, it communicates a '0' Grid-component value to the 'T'-Smart grid. (Consider Appendix A for more information.) This is shown in the first column of figure 5.43.

In the second column of figure 5.43, one can see that the grid supplied load 1 with all its requested energy, except for the last 0.5s when load 2 used all of source 1's energy resulting in load 1 being shed. The supply priority throughout this time was 20, which is the supply priority of source 1. The grid demand value was 0.8 up until 2.5s, as previously explained.

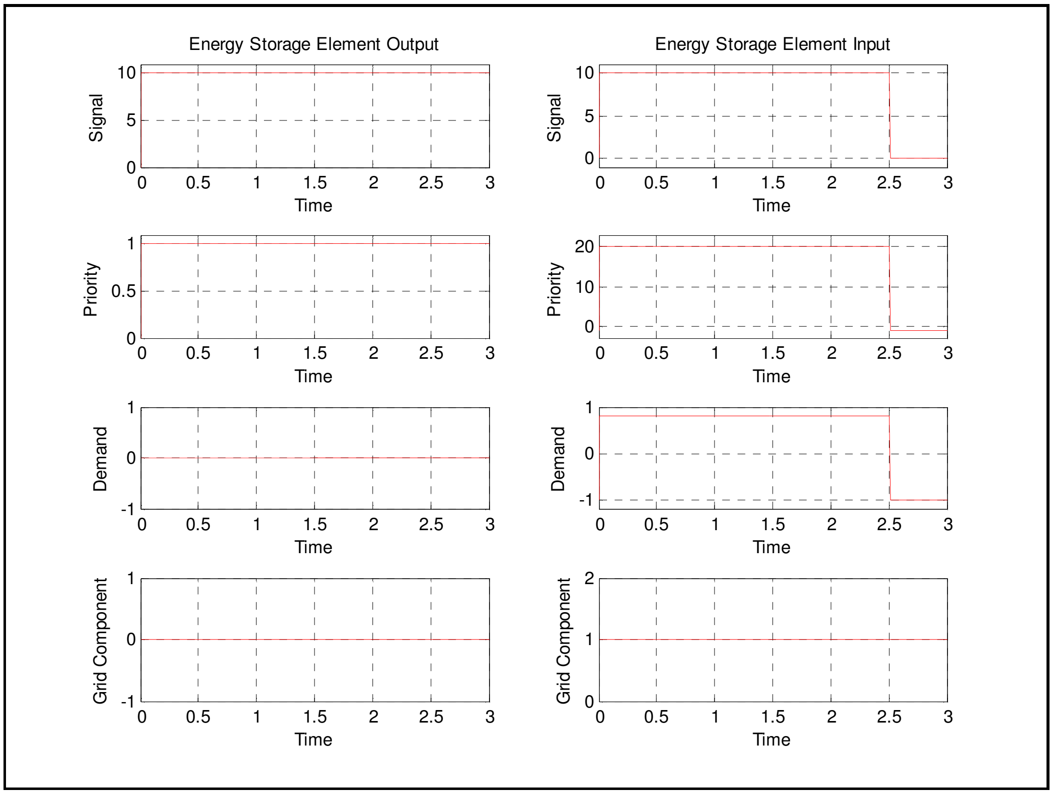

Fig 5.43: Outputs of the circuit - The Energy storage element's output to the grid and Input from the grid - Example 9 - Energy storage element's second mode of operation

Finally, it is supplied by energy so the Grid-component value is '1' (because it is emulating a load. Consider Appendix A for more information.). Note that during 1.5s to 2s, the request for 10 units of energy by the energy storage element was still met by the grid and this energy was simply conducted to the load, and no part of it was stored in the energy storage element.

Also note that if load 2 in the final 0.5s increased its energy requirements from 10 to 20 units of energy, instead of 25 units of energy, the outcome would have been the same for the energy storage element and its operation. The reason for this is that in its current operation, its emulating a load and an entire load is shed if the grid cannot supply it. Hence, the entire energy storage element is disconnected from the grid and there is no chance for it to store the 5 units of energy (Source 1 - Load 2 [new value] = 25 - 20 = 5 units of energy) for future use. This is however not the case when the energy storage element is connected in its third mode of operation as seen in the next example.

5.11 Example 10 – Energy storage element's third mode of operation

In this example, it is shown how the energy storage element would operate on its own, ensuring energy is stored in relative off-peak time and then discharge in relative on-peak time, automatically. This is achieved by simply storing excess energy when no load in the circuit is using it, and discharging when there is a shortfall in energy. (This is the energy storage Element's third mode of Operation.) Consider figures 5.44 to 5.49.

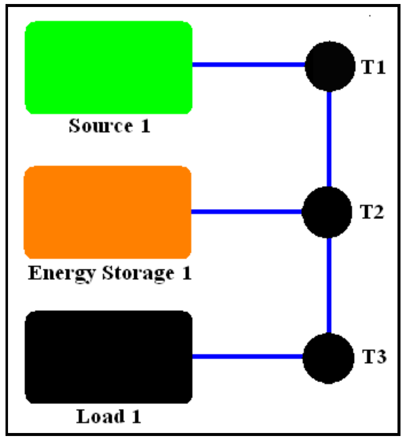

Fig 5.44: Simple representation of the circuit - Example 10 - Energy storage element's third mode of operation

In this example, there are three 'T'-components, one connected to a source, one to an energy storage element and the last one to a load. The energy storage element is set as follows (as seen in figure 5.45); Saturation level is at a 1000 units of energy, its supply priority is 10, its maximum discharge limit is 500 units of energy for a single simulation period / grid state (0.01s) and its maximum charge limit is 30 units of energy for a single simulation period / grid state (0.01s).

Its PLD is set at values 100 and 10, which means it would only discharge energy if it has been fully charged (to 100% of saturation) and if its internal stored energy level falls below 10%, then it would first charge up again (to 100%) before considering discharging. The demand zone of all 'T'-components in this example is set at 2 components above and below for the simulation. There are also no grid (infrastructure) limitations in this example.

In this simulation Source 1 supplies energy in a sinusoidal waveform, with a DC offset of 10 and the sinusoidal waveform itself has amplitude of 5 with a frequency of 10 Hz. The source has this energy available in this form for the entire 3 seconds of the simulation and its supply priority is 20. Load 1 has a request for 5 units of energy from the grid for the first two seconds of the simulation, and thereafter 20 units of energy for the last simulation second. Its load priority is 1 throughout the simulation.

From figure 5.47 it is seen that for the first simulation second the source supplies energy in its sinusoidal form at a supply priority of 20 and demand of the grid is lowest when its supply is at its peak and highest when it is at its lowest supply point. When the source supplies 15 units of energy (peak) and load uses 5 units of energy the grid has a demand of 5/15 = 0.333. Similarly, when the waveform reaches its low of 5 units of energy, the demand increases to 5/5 = 1. This continues for the entire first second of the simulation and the load receives its 5 units of requested energy, at a supply priority of 20 from the source and its demand is exactly the same as explained earlier. Note that the load is still in-zone in this example.

As explained in Chapter 4, when the energy storage element charges, it does not impact on the demand of the system. Thus, the energy storage element can charge a maximum of 30 units of energy, however there is only 15 - 5 = 10 units of energy available, when the supply is at its peak, and this is then stored. As the sinusoidal waveform drops to 5 units of energy, the available energy to store drops down to 5 - 5 = 0 available energy units.)

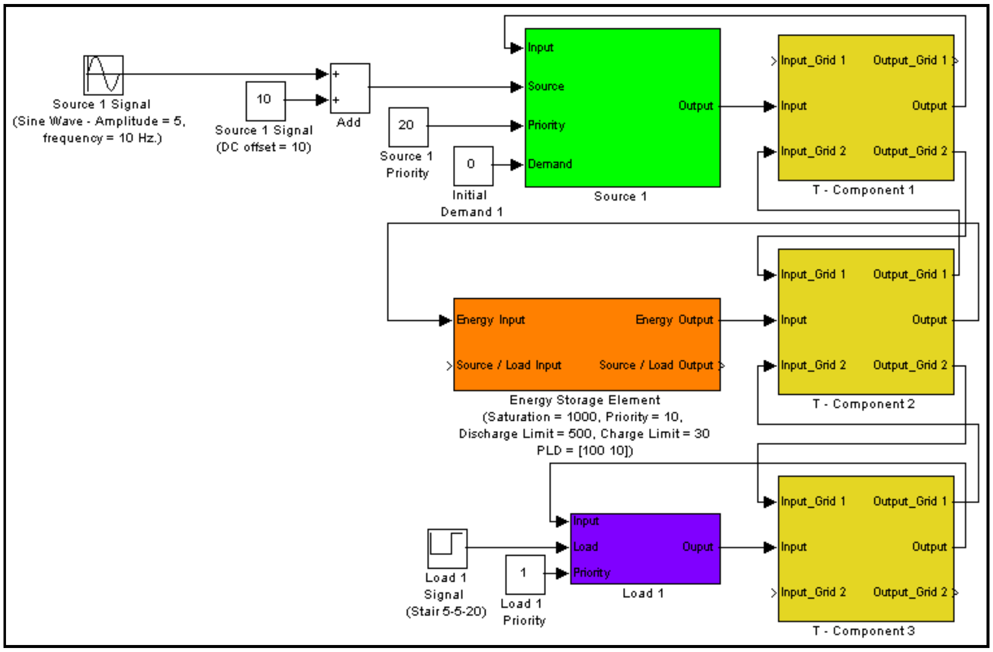

Fig 5.45: Simulink representation of the circuit - Example 10 - Energy storage element's third mode of operation

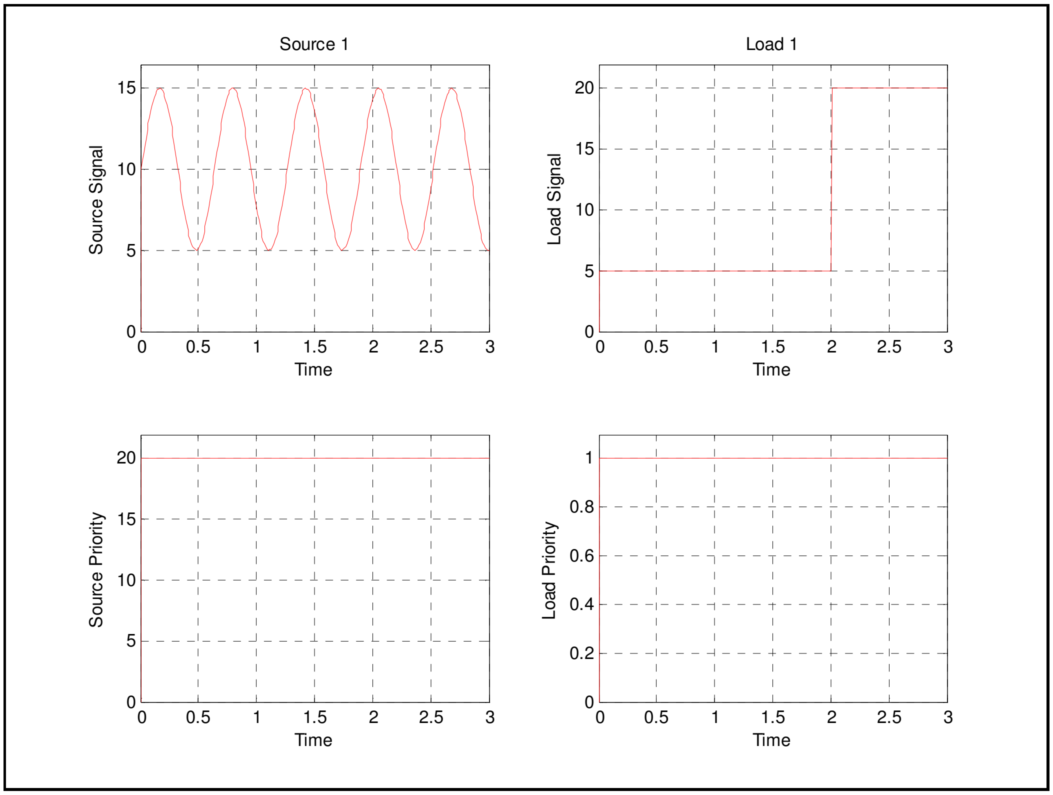

Fig 5.46: Inputs to the circuit - Example 10 - Energy storage element's third mode of operation

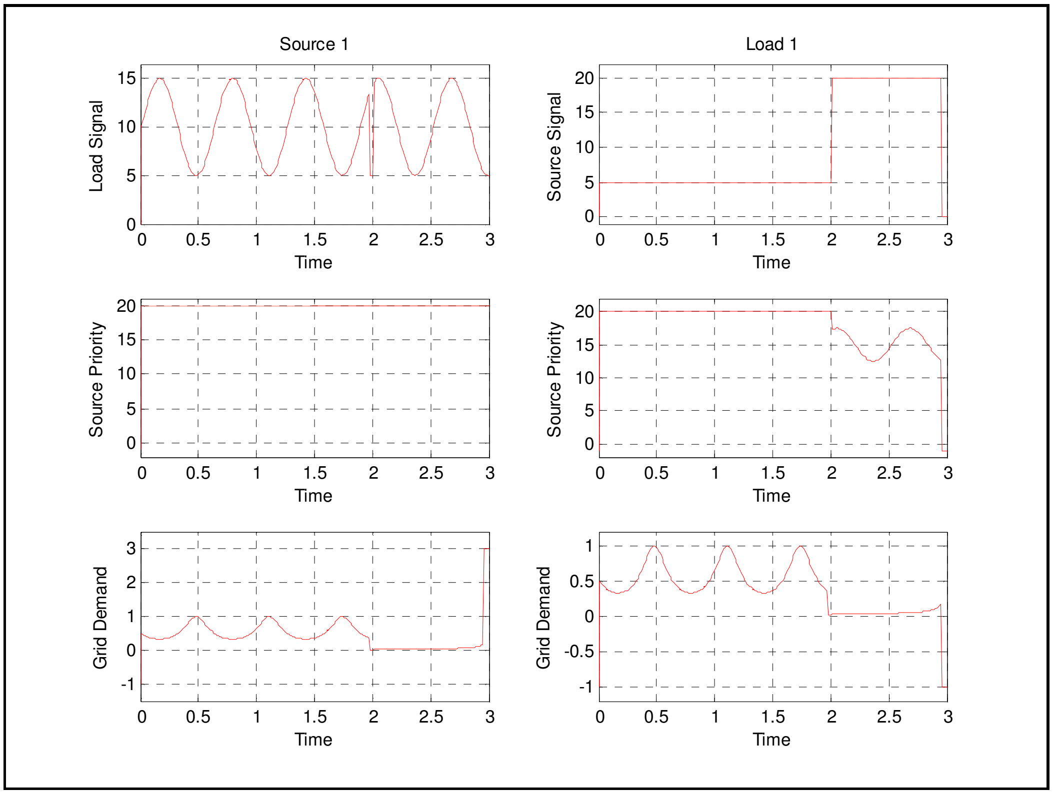

Fig 5.47: Outputs of the circuit - Example 10 - Energy storage element's third mode of operation

The second simulation second, it exactly as the first and the storage element is still charging up in the background without the knowledge of the Grid-components. At 1.98 seconds, the energy storage element reaches saturation and it only needs to supply 5 units of energy to load 1 as requested, at a supply priority of 20. The demand at this time now has to factor in the available energy form the energy storage element and hence the demand from seconds 1.98 to 2 seconds if the sinusoidal waveform is at its peak is, 5 (Load 1) / [15 (Source 1) + 500 (Energy storage element)] = 0.0097. The loads' output waveform (load request) is exactly the same as for the first simulation second, only the grid demand value drops to the value explained earlier.

For the final simulation second, the load requests 20 units of energy which is beyond the supply capability of the source. (The source can only supply a maximum of 15 units of energy, when the sinusoidal waveform is at its peak.) Hence, energy is discharged from the energy storage element to meet the load's request.

As can be seen from figure 5.47, the source supplies its energy for the entire last simulation second at a supply priority of 20 but on the demand graph, the grid demand becomes 3 in the last 0.04 second as the energy storage element's available energy depletes and the load is shed. Note however, the source kept on supplying its sinusoidal waveform during this last 0.04 seconds, because it is charging the energy storage element.

The load, in the last simulation second, received its energy but is shed for the last 0.04 seconds as described earlier. The supply priority at which the load is supplied varies only in amplitude with the source's supply waveform. This is because the 'T'-Smart grid favours energy from a source which is available, rather than energy from an energy storage element, as energy storage elements can be expensive to operate and it would be wasteful to store and use energy from it, rather than using the available source.

When the supply waveform is at its peak of 15, the supply priority is 15 / 20 * 20 (Source supply priority) + 5 / 20 * 10 (Energy storage element supply priority) = 17.5. Similarly, when the waveform is at its lowest, the supply priority to the load is 5 / 20 * 20 (Source supply priority) + 15 / 20 * 10 (Energy storage element supply priority) = 12.5.

For both the load and the source, the grid demand during this time starts with 20 (Load 1) / [(15 (Source 1) + 500 (Energy Storage Element)] = 0.039. The energy storage element will stop supplying energy when the energy level drops through 10% of the saturation mark. In this case, it dropped in one 0.01s simulation increment to 96.9 units of energy which made the demand 20 (Load 1) / [(15 (Source 1) + 96.9 (Energy Storage Element)] = 0.178 before it shed load 1. Then, as indicated previously, in the last 0.04 seconds the source's grid demand graph indicates a '3' because a load is shed (an intervention occurred) and the source supplies all its energy to the energy storage element. (Thus it is a demand of 1, incremented with a value of 2 because of the intervention.). The load indicates a '-1' during this period as it is shed.

Note how significant it was for the load to be shed, even before the grid demand reached 20%. One would expect immanent load shedding or failure of energy storage elements at a demand of 90% or more and not at a low level of 0.178 (or 17.8%). This example highlights that systems with large energy storage elements, and of which the loads are greater than the sources in a given period, may experience the same problem. It is believed that reducing the setting of the minimum discharge value (in this case 10% of saturation) may not be a solution as the percentage level may be a physical chemical / mechanical limit which cannot be reduced. Instead, an exponential curve which increases the demand exponentially towards the depletion of the energy storage element might be a means to better warn Grid-components of immanent supply failure.

Figure 5.48, depicts what is explained earlier. The energy storage element charges up for the first 1.98 seconds after which it reaches saturation for 0.02 seconds. After this, it discharges until it reaches the 10% of its saturation level at 2.96 seconds and then stops discharging energy and starts charging energy again.

Also, as can be seen in figure 5.48, when the source's sinusoidal waveform is at its peak it stores more energy and when the sinusoidal waveform is at its lowest point, when no energy is stored. This then creates the sinusoidal charging and discharging curve.

As will be seen in the next section, in the first 2s the energy storage element receives energy in a sinusoidal form of which the RMS value is 5 units of energy (estimate), per 0.01 simulation increment / grid state (determined through inspection). Hence, the energy storage element charged to 2s / 0.01s * 5 = 1000 units of energy in just under 2s. Similarly, it discharged at an RMS rate of 10 units (estimate, determined through inspection) of energy per simulation period / grid state and hence it fully discharged within 1000 / 10 * 0.01s = 1s, as seen in the last simulation second. (When comparing that which was calculated above to the actual times when these events occurred, as seen on the graph, the difference is small and is only because the RMS of the signal was estimated.)

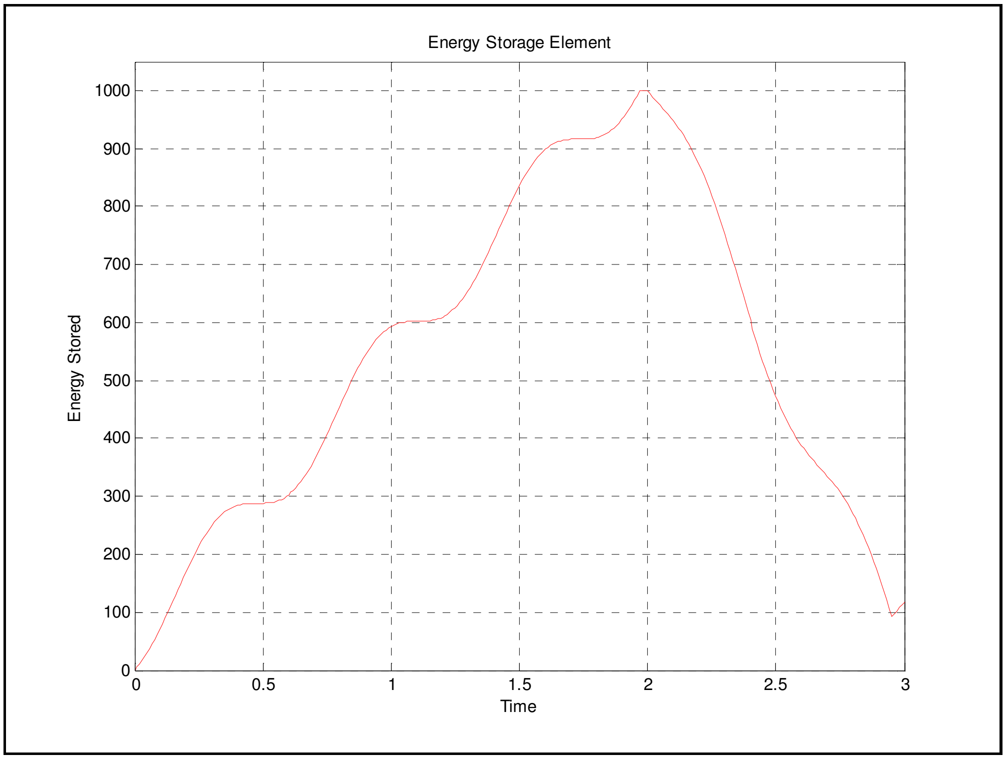

Fig 5.48: Outputs of the circuit - Energy level inside Energy storage element - Example 10 - Energy storage element's third mode of operation

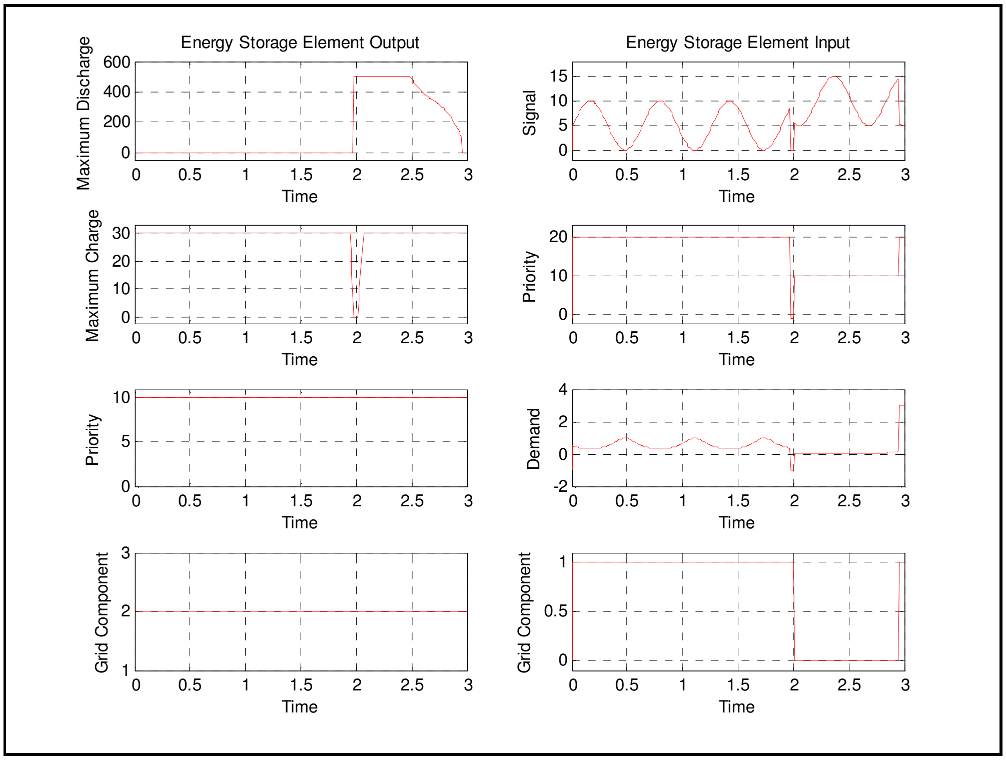

Fig 5.49: Outputs of the circuit - The Energy storage element's output to the grid and Input from the grid - Example 10 - Energy storage element's third mode of operation

Finally, figure 5.49, depicts how the energy element communicates with the grid. As can be seen in the bottom left corner, the Grid-component value is '2' (Consider Appendix A for more information). Hence, the grid knows it is an energy storage element operating in its third mode of operation and not a source or a load. (Note, in the previous two modes of operation, the energy storage element was emulating a source or a load.)

Because of this, the first three variables sent to the grid are not energy supply / requirement, priority and demand but instead it is maximum energy that can be discharged, maximum energy that can be charged and supply priority (as described in Appendix A). Hence, for the first 1.98 seconds the energy storage element communicated to the grid that it had no energy available, it could charge at a rate of 30 units of energy (but at most it only received 15 - 5 = 10 units of energy on the sinusoidal waveform peak) and its supply priority is 10 as an energy storage element supplying the grid. (This is shown in the first column.)

Then, as seen in the second column, the grid responded and supplied the energy storage element with a sinusoidal waveform of energy, at a supply priority of 20 from source 1, and the grid demand varied as explained earlier. Thus, there was energy flowing into the energy storage element so the grid was a source and the Grid-component value is a '1' (bottom right) in the first 1.98 seconds.

In the seconds 1.98 to 2 seconds, the energy storage element reaches saturation and then communicated to the grid it had 500 units of energy to supply (irrespective of grid limitations), it has no charging requirements and it can supply the energy at a priority of 10. (This is depicted in the first column.) In turn, the grid responded in the 0.02 seconds with no supply requirements, it assigned it a '-1' priority and demand value to show it is disconnected from the grid, and communicated a '0' (load) Grid-component value in case energy needs to be discharged from it. (This is depicted in the second column.)

In the seconds 2 to 2.96, the energy needs to be discharged from the energy storage element in order to supply the load connected the grid. During this time, the energy storage element communicated to the grid its energy it could discharge and as can be seen from figure 5.49. After 2.48 seconds 500 units of energy was already supplied and the available energy inside the energy storage element fell below the maximum discharge limit of 500, and hence one could see the available energy drop as it approaches 2.96 seconds.

Similarly, initially when the energy storage element started discharging, the charging requirements communicated to the grid increased until it reached the maximum set value of 30. The supply priority remained at 20 with the Grid-component value of at '2' as shown. (This is depicted in the first column.)

As can be seen in the second column, the energy waveform supplied to the grid is also sinusoidal as the input waveform, but is 180° out of phase with it because the source's waveform has a higher priority than that of the stored energy, as explained earlier. Hence, when the source's sinusoidal waveform is at its peak, the energy storage element is at its lowest supply point and vice versa to meet the energy requirement of the load together. The supply priority of the energy storage element is 10, as set initially. The grid demand value is very low as calculated earlier and increases with time up until 2.96 seconds. During this time, the grid communicates a '0' Grid-component value (load) to it, to indicate it needs to discharge energy from it. (Consider Appendix A for more information.)

In the final 0.04 seconds, the energy storage element is depleted and starts with its charging cycle again. During this time, as seen in the first column, the energy storage element has no energy to discharge, but can charge energy up to a quantity of 30. It supply priority and Grid-component value remain constant at 10 and 2 respectively. As can be seen in the second column, the energy storage element is supplied by the source in the last 0.04 seconds, while load 1 is shed. It is supplied at a priority of 20 and the demand during this time is 3 to show that a load is shed (intervention). The Grid-component value returns to a '1' value (source) to show that the grid is a source to the energy storage element it is charging. (Consider Appendix A for more information.)

5.12 EXAMPLE 11 - ENERGY STORAGE ELEMENT IN A SUB-GRID

This example aims to show how the energy storage element would operate in its third mode of operation if a customer had its own internal grid and only needed to be serviced by the energy storage element and not by the external grid as well. Hence, the energy storage element only maintains its grid or sub-grid connected to it, and further sub-grid downwards connected to it, but not upwards as explained in Chapter 4.

Figure 5.50 depicts a main-grid with loads and sources summated together and represented by Source 2 to and Load 2 and an imbedded grid connected to 'T2'. The embedded grid also has sources and loads summated together which is represented by Source 1 and Load 1 and this embedded (sub-) grid is connected and maintained by the energy storage element. Consider figures 5.50 to 5.55.

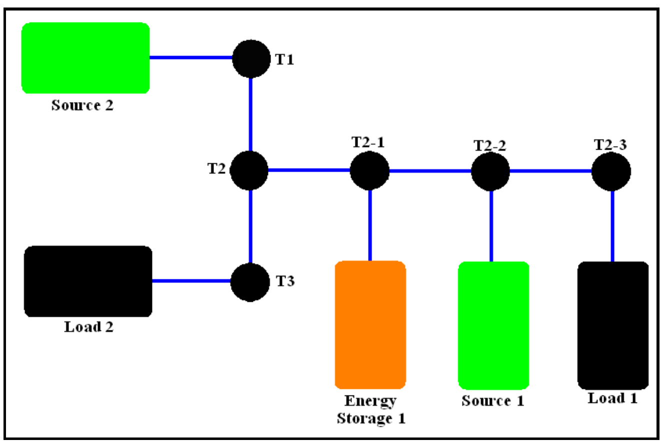

Fig 5.50: Simple representation of the circuit - Example 11 - Energy storage element in a sub-grid

The main-grid of the example comprises of three 'T'-components ('T1' to 'T3') which connected to a sub-grid ('T2-1' to 'T2-3').The energy storage element in the sub-grid is set as follows (as seen in figure 5.51); Saturation level is at a 1000 units of energy, its supply priority is 10, its maximum discharge limit is 500 units of energy for a single simulation period / grid state (0.01s) and its maximum charge limit is 30 units of energy for a single simulation period / grid state (0.01s).

Its PLD is set at values 100 and 10 as the previous examples. The demand zone of all 'T'-components in this example is set at 2 components above and below throughout the simulation. There are also no grid (infrastructure) limitations in this example. In addition, where the sub-grid connects to the main-grid, both the source and load priority values are defined as 5 for the sub-grid.

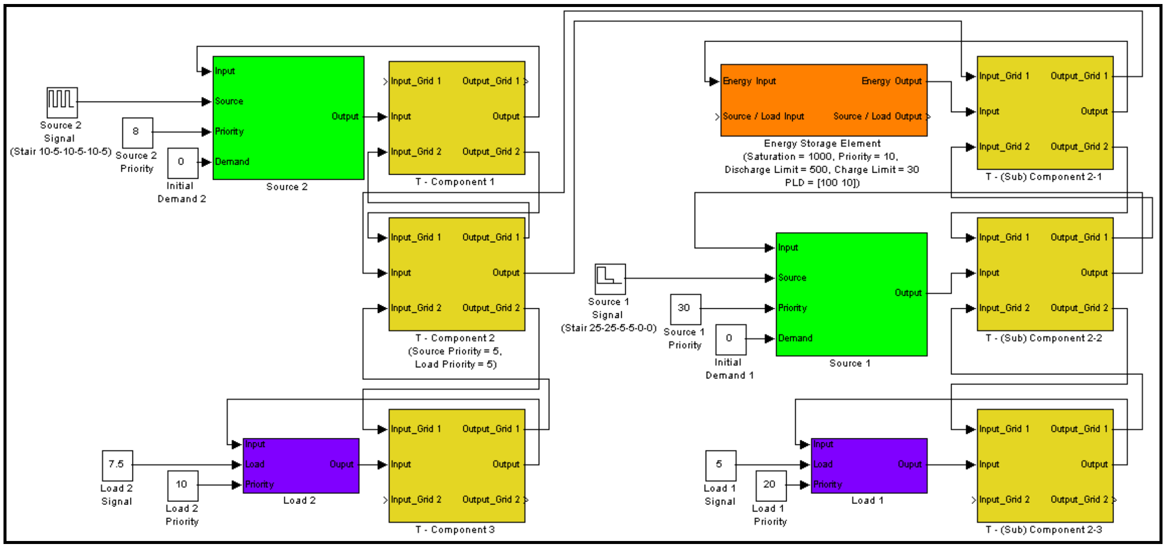

Fig 5.51: Simulink representation of the circuit - Example 11 - Energy storage element in a sub-grid

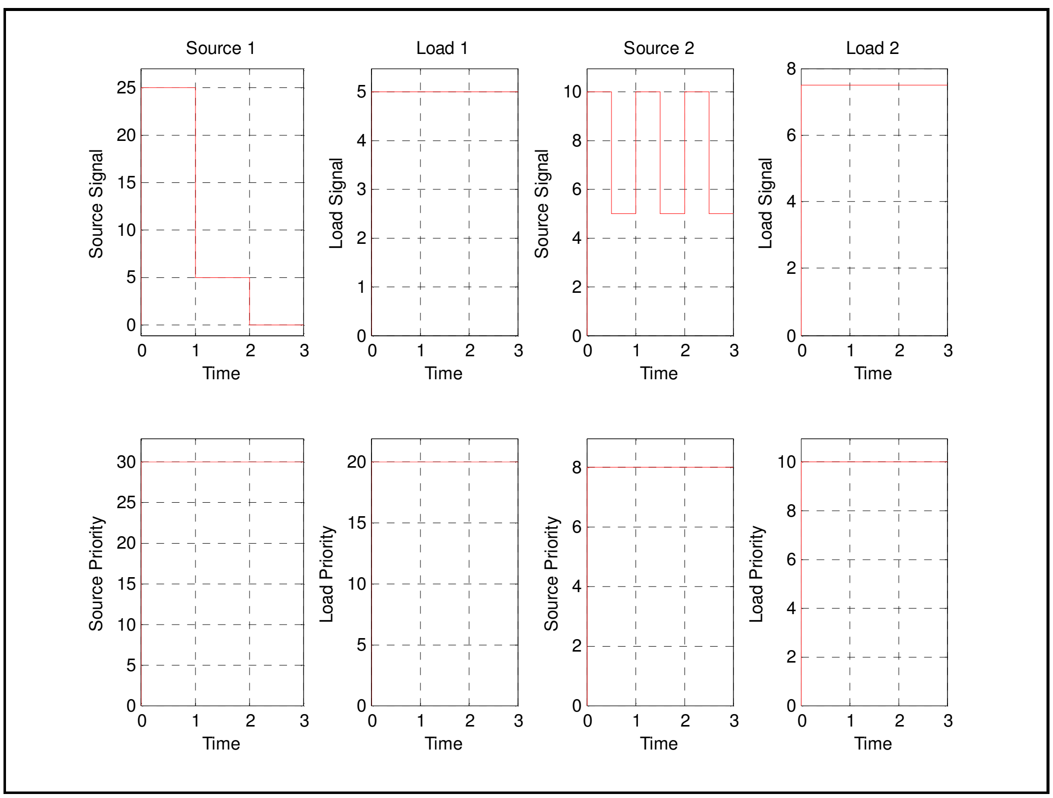

Fig 5.52: Inputs to the circuit - Example 11 - Energy storage element in a sub-grid

As indicated in figure 5.51 and figure 5.5, Source 1 supplies 25 units of energy for the first second, 5 units of energy for the next second and then 0 units of energy for the final simulation period, at a constants supply priority of 30. Load 1 request 5 units of energy at a load priority of 20 throughout the simulation period. Source 1 and Load 1 is connected in a sub-grid with the energy storage element while Source 2 and Load 2 are connected to the main-grid. Source 2 oscillates between supplying 10 units of energy and 5 units of energy every 0.5s throughout the simulation at a supply priority of 8. Load 2 request 7.5 units of energy at a load priority of 10 throughout the simulation.

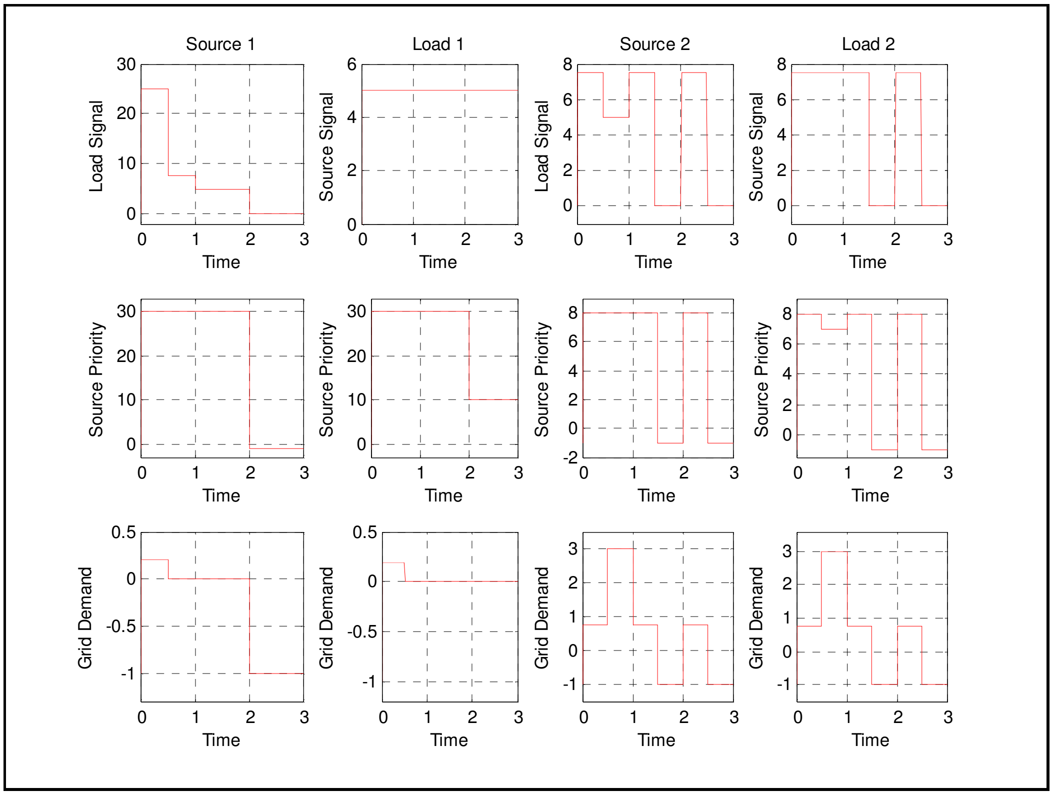

Fig 5.53: Outputs of the circuit - Example 11 - Energy storage element in a sub-grid

In the first 0.5 seconds, for the sub-grid, Source 1 supplied 25 units of energy to Load 1 (5 units of energy requested) and the energy storage element. The supply priority of Source 1 is 30, which is also the priority at which the load is supplied. The demand in the sub-grid is 5 / 25 = 0.2 during this period. (Note, as previously explained, the energy supplied to the energy storage element does not impact on the demand of the grid.) The energy storage element is fully charged in this 0.5 second period, as will be seen later.)

In the first 0.5 seconds, for the main-grid, Source 2 supplied 7.5 units of energy to Load 2, meeting its total energy request. The supply priority of Source 2 is 8, which is also the priority at which the load is supplied. The demand in the main-grid was 7.5 / 10 = 0.75 during this period.

In the next simulation period, from 0.5s to 1s, in the sub-grid, Source 1 supplies Load 1 with 5 units of energy and Load 2 (main-grid) with 2.5 units of energy at a supply priority of 30. The priority at which Load 1 is supplied is thus 30. Because the energy storage element is already fully charged by 0.5 s (previous 0.5s simulation period), it now has 500 units of energy available, as will be seen later. The demand is thus now, 5 (Load 1) / [25 (Source 1) + 500 (Load 1)] = 0.0095. (Note that the energy exported to the main-grid does not impact on the demand of the sub-grid, as explained in Chapter 4.)

Similarly in the period from 0.5s to 1s, in the main-grid, Source 2 supplies the Load 2 with 5 units of energy at a supply priority of 8 and Source 1 supplies 2.5 units of energy at a supply priority of 5, due to the setting where the sub-grid connects to the main-grid. Note that Source is exporting energy to the main-grid, to meet the load requirement of the main-grid, and during this period, energy did not come from the energy storage element in the sub-grid.
Load 2 thus has a supply priority equal to 5 / 7.5 * 8 + 2.5 / 7.5 * 5 = 7. The demand in the main-grid for both Source 2 and Load 2 is '1' because the load request is greater than the energy available from the source in the main-grid, and hence this value is incremented by two to show that energy is obtained from an external sub-grid (an intervention occurred) and thus the value becomes '3'.

For the simulation period, 1s to 1.5s, in the sub-grid, Source 1 supplies 5 units of energy to Load 1, at a supply priority of 30. The demand during this period is 5 / (5 + 500) = 0.0099, due to the energy storage element.

For the same simulation period, 1s to 1.5s, in the main-grid, Source 2 supplies 7.5 units of energy to Load 2, at a supply priority of 8. The demand during this period is 7.5 / (10) = 0.75.

In the simulation period 1.5s to 2s, in the sub-grid, Source 1 supplies 5 units of energy to Load 1, at a supply priority of 30. The demand during this period is 5 / (5 + 500) = 0.0099, due to the energy storage element. This is exactly the same as the previous simulated period and note that there is no extra energy to be exported to the main-grid. Also, due to way the 'T'-Smart grid is programmed, as explained in Chapter 4, the energy storage element does not assist the main-grid as its function is only to maintain the sub-grid(s).

In the same simulation period, 1.5s to 2s, in the main-grid, Source 2 cannot meet the load requirement of Load 2 and hence Load 2 is shed and Source 2 is disconnected. (As mentioned, no spare energy is available from the sub-grid, to be used in the main-grid.) Hence, the supply priority and demand of Source 2 and Load 2 is '-1' during this period.

Note that the energy storage element has charged until it reached saturation in the first 0.5 seconds of the simulation and has not charged or discharged between 0.5s and 2s, as will be seen later.

For the period 2s to 2.5s, in the sub-grid, Source 1 has no energy available and hence Load 1 receives energy from the energy storage element. Hence, Source 1's priority and demand is '-1' during this period. Load 1 is supplied by the energy storage element which has a source priority of '10' and the sub-grid demand is 5 / 500 = 0.1.

For the same period, 2s to 2.5s, in the main-grid, Source 2 supplies 7.5 units of energy to Load 2, at a supply priority of 8. The demand during this period is 7.5 / (10) = 0.75. This is exactly the same result as for the period 1.5s to 2s.

For the final simulation period, 2.5s to 3s, in the sub-grid, the grid conditions stay exactly the same as in the previous simulation period from 2s to 2.5s.

For the same final simulation period, 2.5s to 3s, in the main-grid, the grid conditions are the same as in the simulation period from 1.5s to 2s.

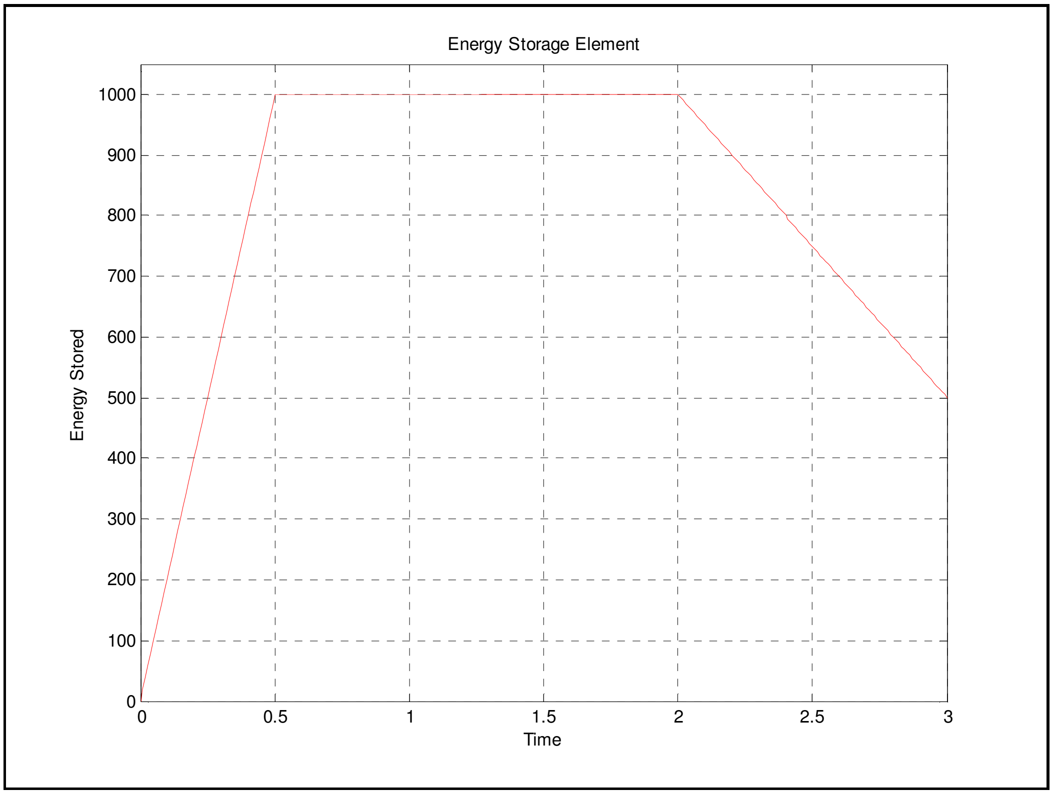

Fig 5.54: Outputs of the circuit - Energy level inside Energy storage element - Example 11 - Energy storage element in a sub-grid

Consider figure 5.54. As explained, the energy storage element is charged within the first 0.5s, and then left with the stored energy for 1.5s after which it is discharged it in the last 1s.

In the first 0.5s there are 20 units of energy in excess in the sub-grid which is used to charge the energy storage element. The saturation level of the energy storage element is a thousand units and the simulation increments / grid states are 0.01s. Hence, 0.5s / 0.01s * 20 = 1000 units of energy stored in 0.5s

In the final simulation second, the sub-grid uses a 5 units of energy every 0.01 simulation increment / grid state. The energy storage element is charged to its saturation level of a 1000 units of energy. Hence, 1000 – [1s / 0.01s * 5] = 500 units of energy left at the end of the simulation period.

Figure 5.55, depicts the input and output communication with the sub-grid only.

In the first 0.5s (first column), it had no energy to discharge and only requested to receive a maximum of 30 units of energy at a time. Its supply priority is 20 and it communicated to the sub-grid that it is an energy storage element (operating in the third mode of operation) by using a'2' for the Grid-component value. (Consider Appendix A for more information.) The second column in figure 5.55 shows that the grid supplied it with 20 units of energy at a supply priority of 30 when the sub-grid demand was 0.2, as previously explained. The input Grid-component value is a '1', because the grid is a source to the energy storage element. (Consider Appendix A for more information.)

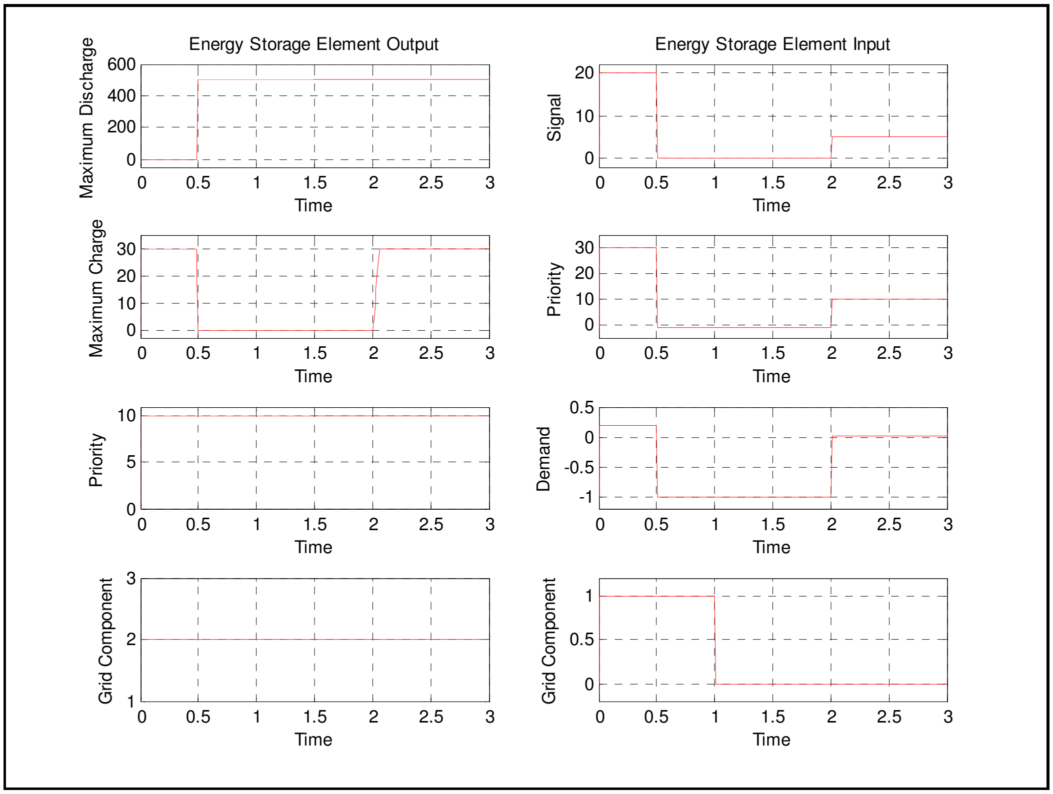

Fig 5.55: Outputs of the circuit - The Energy storage element's output to the grid and Input from the grid - Example 11 - Energy storage element in a sub-grid

For the period 0.5s to 2s, depicted in the first column of figure 5.55, the energy storage element had 1000 units of energy to supply to the grid, but could only discharge a maximum of 500 units at a time. It did not require any energy during this period, as it is saturated and there is no energy being discharged from it. It supply priority remained '10' and its Grid-component value at '2'.

In the second column, it is seen that the energy storage element supplies no energy during this period, and hence the signal is zero, the priority and demand is '-1'. The only exception is that in the period 0.5s to 1s; there was excess energy and the grid thought it could charge the energy storage element before realising it is saturated. Hence, in that period the Grid-component value is '1'. However, in the period 1s to 2s, the grid realised that demand is matching the supply and that it might increase. Hence, the energy storage element is switched to a '0' Grid-component value in case it needs to discharge energy from it.

In the final simulation second, first column, the internal energy (1000 units available) never went below the maximum discharge limit of 500 units of energy, so it still communicated to the grid that it had a 500 units of energy available (Discharge limit). Because it was discharging energy to Load 1 during this period, its request for energy (to charge again) increased from zero until its maximum charge limit of 30 units. It supply priority remained '10' and its Grid-component value at '2'. In the second column, one can see that during this period, it only discharged '5' units of energy per simulation increment / grid state, at a priority of '10' while the sub-grid demand was 0.01 as explained earlier. Because it is discharging, the sub-grid is a load to it and the Grid-component value communicated to it is a '0'.

The example has thus shown that a customer can store and preserve energy for its own use, if the customer owned a sub-grid grid, and only excess energy from the generators are sold to the main-grid. This also motivates customers to have their own internal sub-grid as they have the advantage of generating their own reliable energy at a reduced cost with the added ability to sell excess energy. This also reduces the need for infrastructure expansion on the main-grid which can be quite costly in comparison.

5.13 EXAMPLE 12 - A FAULT ON A RADIAL NETWORK

In this example, it is shown how the 'T'-Smart grid would operate in cases where a network is split due to fault level or economic reasons. It is demonstrated how the 'T'-Smart grid will solve the grids until an event such as a fault occurs and then how a new solution would be found (independent from the Control-component) for the separated grids. Consider figures 5.50 to 5.59.

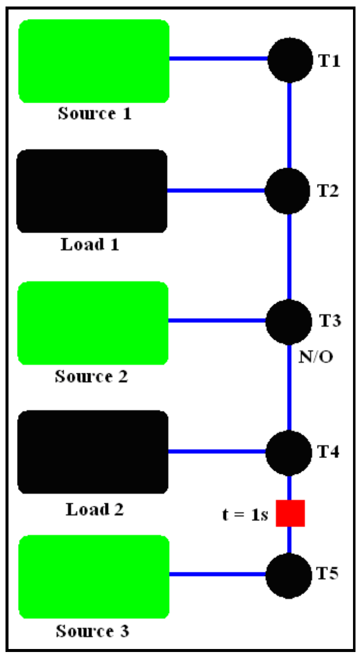

Fig 5.56: Simple representation of the circuit - Example 12 - A fault on a radial network

The circuit comprises of two main-grids connected together through an N/O point, as seen in figure 5.56. 'T'-components 'T1' to 'T3' constitutes one main-grid and 'T4' to T5' another main-grid.

As can be seen from figure 5.57, 'T4' is set with the number of nodes above and below it ('3' nodes above, '2' nodes below), and will only close the N/O point if these node points do not add up, as explained in Chapter 4 and Appendix A.

Also, there is a 'Fault Simulator' block added which will simulate a fault and disconnect the grid at t = 1s. (Consider Appendix A for more information on this block.) Hence, between 0s and 1s, the two main-grid will be solved independently and between 1s and 2s, it will be solved together with 'T5' (and source 3), disconnected from the grid. The demand zone of all

'T'-components in this example is set at 2 components above and below for the simulation. There are also no grid (infrastructure) limitations in this example.

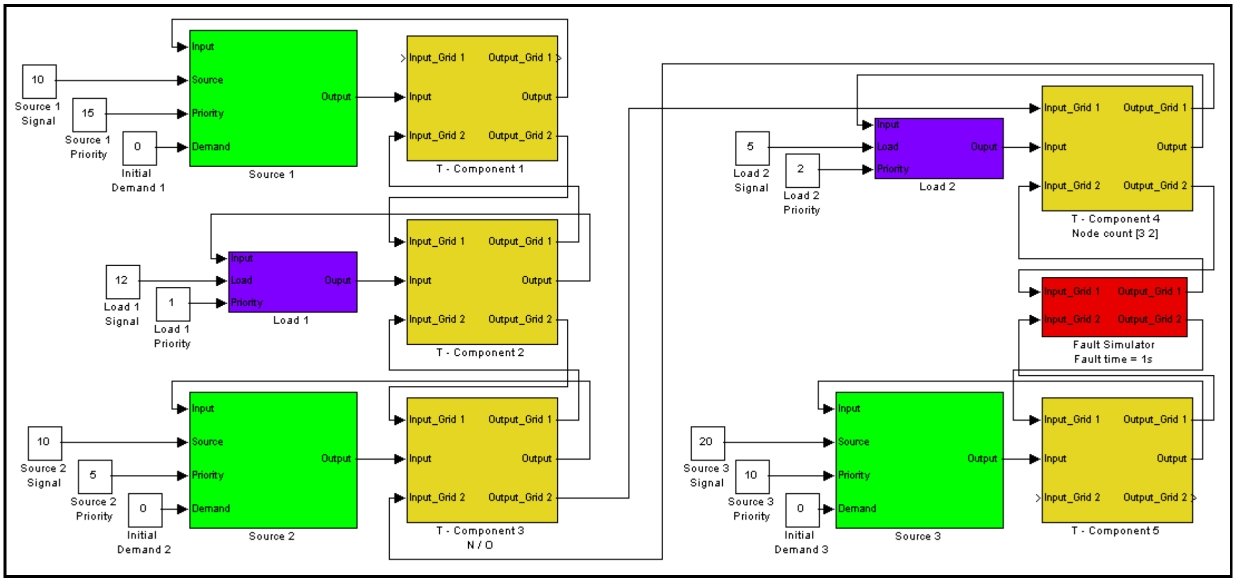

Fig 5.57: Simulink representation of the circuit - Example 12 - A fault on a radial network

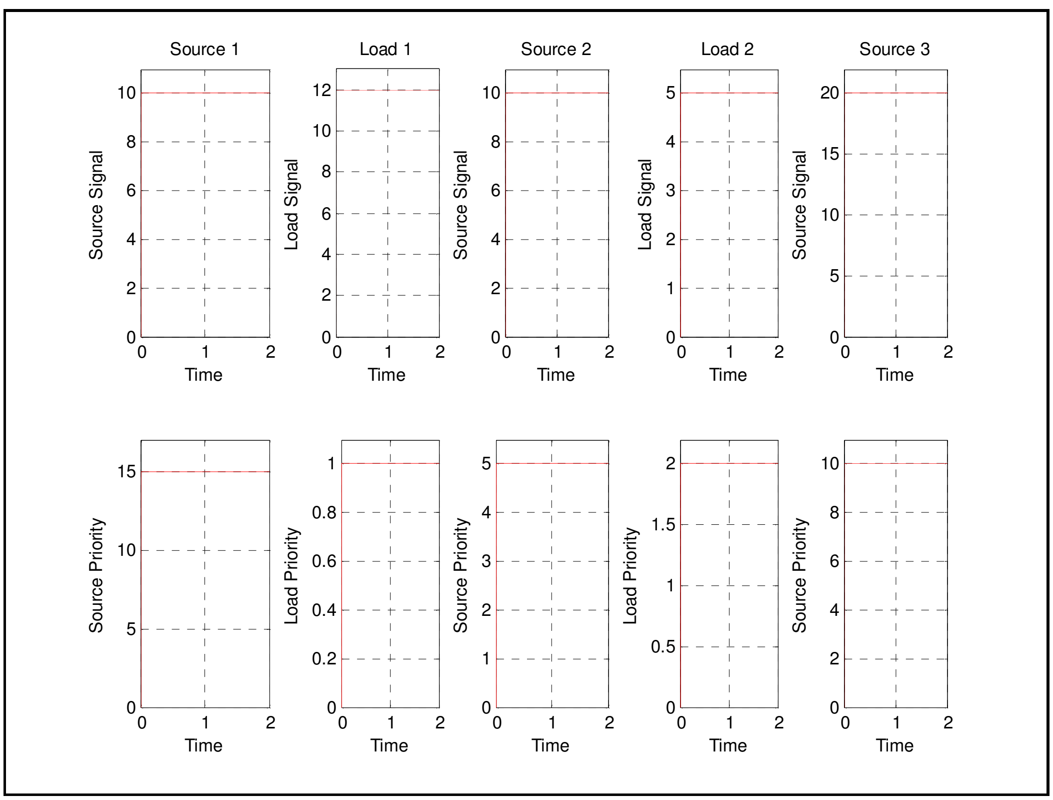

Fig 5.58: Inputs to the circuit - Example 12 - A fault on a radial network

As seen in figure 5.58, Source 1 and Source 2 have 10 units of energy available, at a supply priority of 15 and 10 respectively, throughout the simulation. Load 1 request 12 units of energy at a load priority of 1, throughout the simulation. These Grid-components and respective 'T'-components connected to it constitute the one main-grid. In the other main-grid (separated by a N/O, before the fault occurs at 1s), Source 3 can supply 20 units of energy at a supply priority of 10 and Load 2 request 5 units of energy at a load priority of 2.

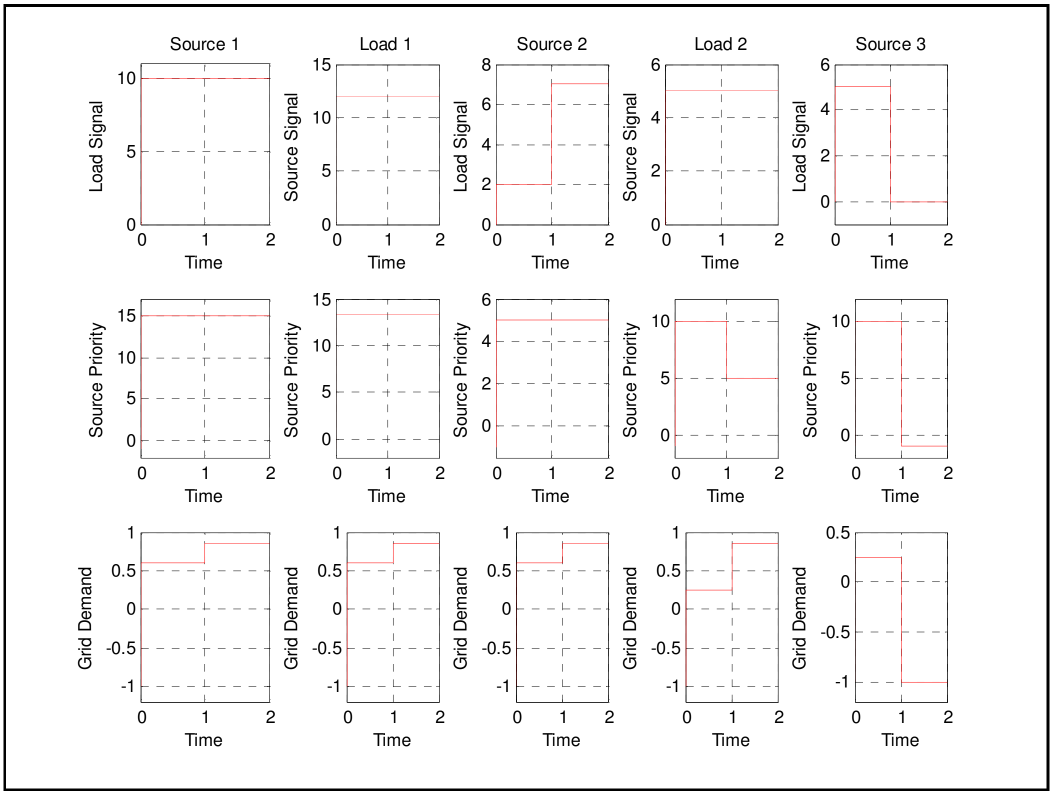

Fig 5.59: Outputs of the circuit - Example 12 - A fault on a radial network

From figure 5.59, for the first main-grid, in the first simulation second, it is seen that Source 1 supplies 10 units of energy and Source 2 supplies 2 units of energy to supply the load of 12 units of energy. The supply priority to the load is 10 / 12 * 15 + 2 / 12 * 5 = 13.333. The demand for the first main-grid is 12 / (10 + 10) = 0.6.

For the second main-grid, in the first simulation second, it is seen that Source 3 supplies 5 units of energy at a supply priority of 10 to Load 2. The demand for the second main-grid is 5 / 20 = 0.25.

When the simulation time reaches 1s, a fault is simulated between point 'T4' and 'T5'. Hence, 'T5' and also Source 3 which is connected to it, is cut-off from the main-grid. 'T4'-recoginizes that the number of nodes below it has changes and hence closes the N/O point towards 'T3'. The grid is now solved as if there was never a 'T5' connected to it.

Thus from figure 5.59, for the first main-grid, in the second simulation second, it is seen that Source 1 supplies 10 units of energy and Source 2 supplies 7 units of energy to supply Load 1 with 12 units of energy and Load 2 with 5 units of energy. The supply priority to the Load 1 is 10 / 12 * 15 + 2 / 12 * 5 = 13.333. Load 2 is only supplied by Source 2 at a supply priority of 5. (This is because the highest priority load is supplied first, but it required supply from two sources. Thus, the second load is supplied from the remainder of the energy from source 2.) Because source 3 is disconnected, its supply priority and demand becomes '-1'. The new combined grid's demand is (12 + 5) / (10 + 10) = 0.85. (Note that all the loads where supplied from 'in-zone' sources.)

5.14 Example 13- A fault on a ring network

In this example, it is shown how the 'T'-Smart grid would operate if the main-grid was connected in a ring, but has a N/O point due to high fault levels or economic reasons. It is then demonstrated how the 'T'-Smart grid will solve this grid in a radial way, and then re-solve it after an event such as a fault occurred. As it will be seen, the solution differs from before the fault to after the fault, even though it is connected in a ring. Consider figures 5.60 to 5.63.

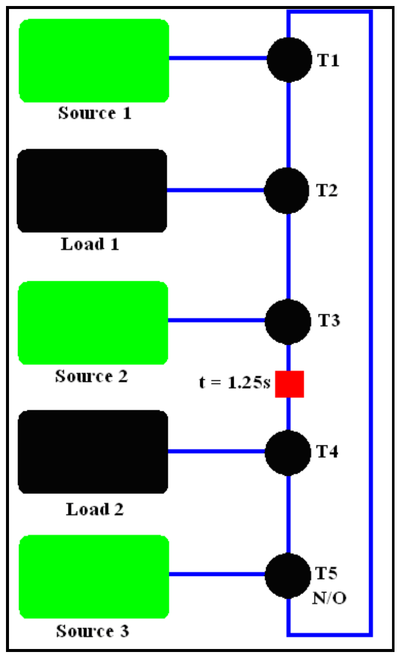

Fig 5.60: Simple representation of the circuit - Example 13 - A fault on a ring network

The circuit comprises of one main-grid, with Source 1, Load 1, Source 2, Load 2 and Source 3 connected together in a radial feed. There is a second connection between 'T5' and 'T1' to make it a closed ring, but it is left as an N/O point. 'T1' is set to count the nodes (5 above, and 5 below it) and ensures that the N/O will close in case of an event such as a fault. The fault simulator is set to introduce a fault at 1.25s in the simulation. Hence, after 1.25s, the connection between 'T3' and 'T4' will be lost and the 'T'-Smart grid will automatically close the N/O point between 'T5' and 'T1'. The demand zone of all 'T'-components in this example is set at 2 components above and below for the simulation. There are also no grid (infrastructure) limitations in this example.

As depicted in figure 5.62; Source 1 supplies 25 units of energy at supply priority of 15, Source 2 supplies 25 units of energy at supply priority of 10 and Source 3 supplies 50 units of energy at supply priority of 5, throughout the simulation. Load 1 has a request for 40 units of energy and its load priority is 1, throughout the simulation. Load 2 has an incremental load request of 10, 20, 30 and 40 units of energy respectively. Its load priority is 2 throughout the simulation.

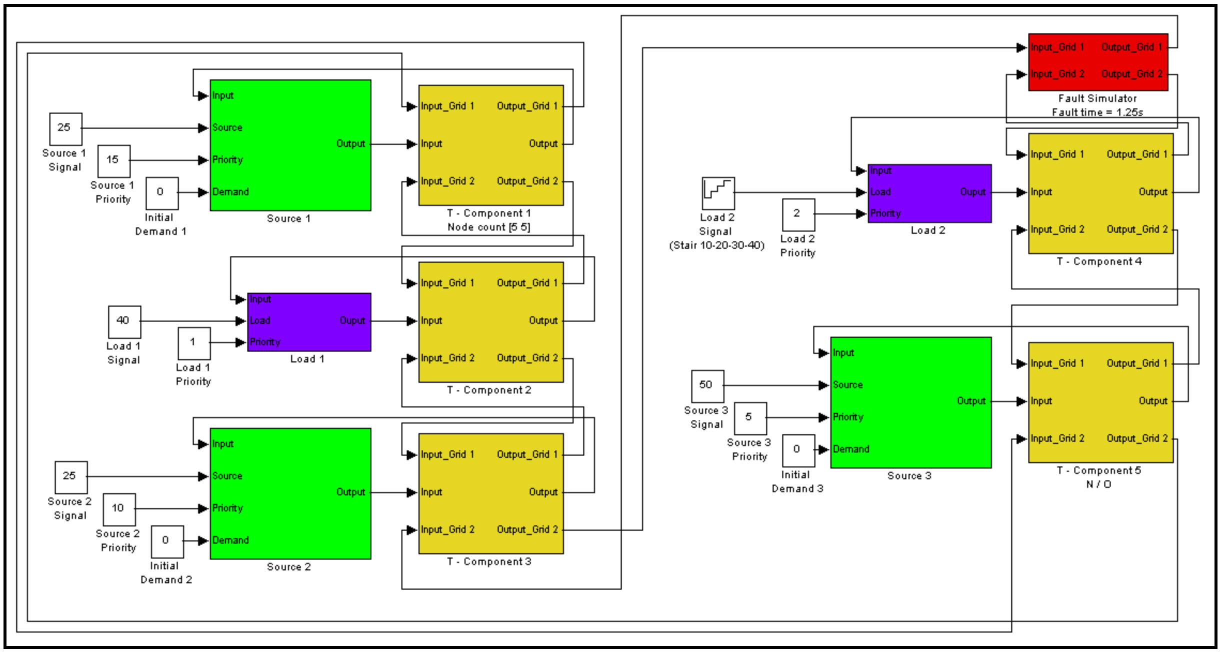

Fig 5.61: Simulink representation of the circuit - Example 13 - A fault on a ring network

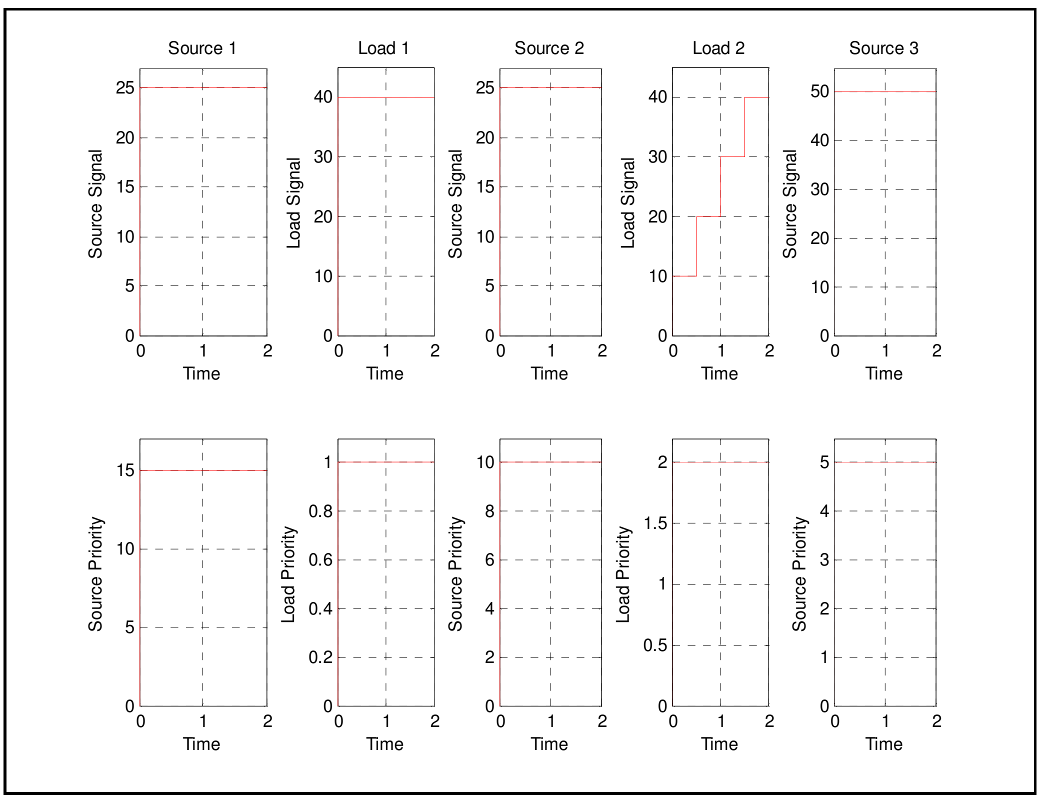

Fig 5.62: Inputs to the circuit - Example 13 - A fault on a ring network

In the period 0s to 0.5s, Source 1 supplies 25 units of energy at a supply priority of 15 and Source 2 supplies 15 units of energy at a supply priority of 10 to Load 1, such that its supply priority is 25 / 40 * 15 + 15 / 40 * 10 = 13.125. Source 2 then supplies 10 units of energy at a supply priority of 10 to Load 2. Source 3's supply is not needed and it is shed. (Its supply priority and demand is thus '-1'.) The grid's demand is (40 + 10) / (25 + 25 + 50) = 0.5.

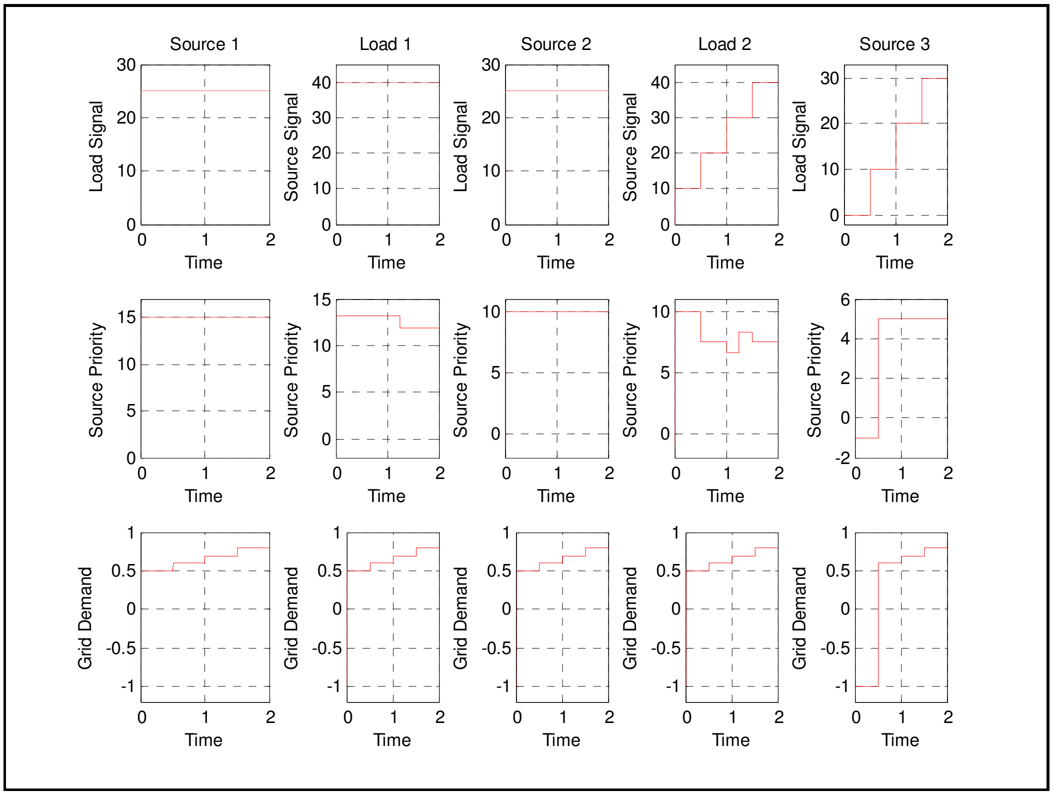

Fig 5.63: Outputs of the circuit - Example 13 - A fault on a ring network

In the period 0.5s to 1s, Source 1 supplies 25 units of energy at a supply priority of 15 and Source 2 supplies 15 units of energy at a supply priority of 10 to Load 1, such that its supply priority is 25 / 40 * 15 + 15 / 40 * 10 = 13.125. Source 2 then supplies 10 units of energy at a supply priority of 10 and Source 3 supplies 10 units of energy at a supply priority of 5 to Load 2, such that its supply priority is 10 / 20 * 10 + 10 / 20 * 5 = 7.5. The grid's demand is (40 + 20) / (25 + 25 + 50) = 0.6.

In the period 1s to 1.25s, Source 1 supplies 25 units of energy at a supply priority of 15 and Source 2 supplies 15 units of energy at a supply priority of 10 to Load 1, such that its supply priority is 25 / 40 * 15 + 15 / 40 * 10 = 13.125. Source 2 then supplies 10 units of energy at a supply priority of 10 and Source 3 supplies 20 units of energy at a supply priority of 5 to Load 2, such that its supply priority is 10 / 30 * 10 + 20/30 * 5 = 6.666. The grid's demand is (40 + 30) / (25 + 25 + 50) = 0.7.

When the simulation time equals 1.25s, the fault simulator is initiated and the connection between 'T3' and 'T4' is lost. The 'T'-Smart grid recognises the fault as the node count has changed, and closes the N/O point between 'T5' and 'T1'. Hence, the grid is solved as if the original arrangement was 'T4' connected to 'T5', connected to 'T1', connected to 'T2', connected to 'T3'.

In the period 1.25s to 1.5s, Source 1 supplies 15 units of energy at a supply priority of 15 and Source 2 supplies 25 units of energy at a supply priority of 10 to Load 1, such that its supply priority is 15 / 40 * 15 + 25 / 40 * 10 = 11.875. (Note that the 'T'-Smart grid is solving the circuit such that the minimal infrastructure capacity will be required, as explained in Chapter 4 and Appendix A.) Source 1 then supplies 10 units of energy (which is the only energy remaining from it) at a supply priority of 15 and Source 3 supplies 20 units of energy at a supply priority of 5 to Load 2, such that its supply priority is 10 / 30 * 15 + 20 / 30 * 5 = 8.333. The grid's demand remains the same, (40 + 30) / (25 + 25 + 50) = 0.7.

In the final period of 1.5s to 2s, Source 1 supplies 15 units of energy at a supply priority of 15 and Source 2 supplies 25 units of energy at a supply priority of 10 to Load 1, such that its supply priority is 15 / 40 * 15 + 25 / 40 * 10 = 11.875. (Note that the 'T'-Smart grid is solving the circuit such that the minimal infrastructure capacity will be required, as explained in Chapter 4 and Appendix A.) Source 1 then supplies 10 units of energy (which is the only energy remaining from it) at a supply priority of 15 and Source 3 supplies 30 units of energy at a supply priority of 5 to Load 2, such that its supply priority is 10 / 40 * 15 + 30 / 40 * 5 = 7.5. The grid's demand is (40 + 40) / (25 + 25 + 50) = 0.8.

Hence, it is seen that if a fault occurs and the 'T'-Smart grid close an N/O to restore supply, then the new solution would differ from the solution prior to the fault. This is because the 'T'-Smart grid always solves in an optimal way such that the minimum amount of energy is transferred across a medium. (This saves on infrastructure expansion costs, conductor losses and maintenance costs in general.)

5.15 EXAMPLE 14 - A FAULT ON A RING CONNECTED SUB-GRID

This example shows how a radially fed main-grid has a sub-grid which can connect to a default point or a secondary connection point in the main-grid, in case of a fault. Again, there may be a multitude of reasons why this network configuration is chosen.

Hence, the 'T'-Smart grid will solve the radial main-grid and the sub-grid as demonstrated earlier. Once the fault occurs, the N/O will be closed, the sub-grid will be split into two sections (due to the fault), and each section will be solved from a different connection point on the main-grid, separately. Again, the solution differs from before the fault to after the fault occurred, even though it is the same sources and loads. Consider figures 5.64 to 5.67.

The main-grid is a radial network comprising of five 'T'-components. 'T1' is connected to a source, 'T3' is connected to a load and 'T5' is connected to another source. 'T4' is normal connection point to a sub-grid comprising of two 'T'-components, one connected to a load and the other to a source. In case of a fault, the sub-grid can close its N/O point towards 'T2' and solve the entire or section of the sub-grid.

In this example, the sub-grid will be split and Load 2 will be solved from 'T4' and Source 3 will be solved from 'T2' after the fault occurred. The fault will occur at 1.25s of the simulation. The node count at 'T4-2' is set at 1 node above and 3 nodes below, as explained in the convention of Appendix A. The demand zone of all 'T'-components in this example is set at 2 components above and below for the simulation. There are also no grid (infrastructure) limitations in this example.

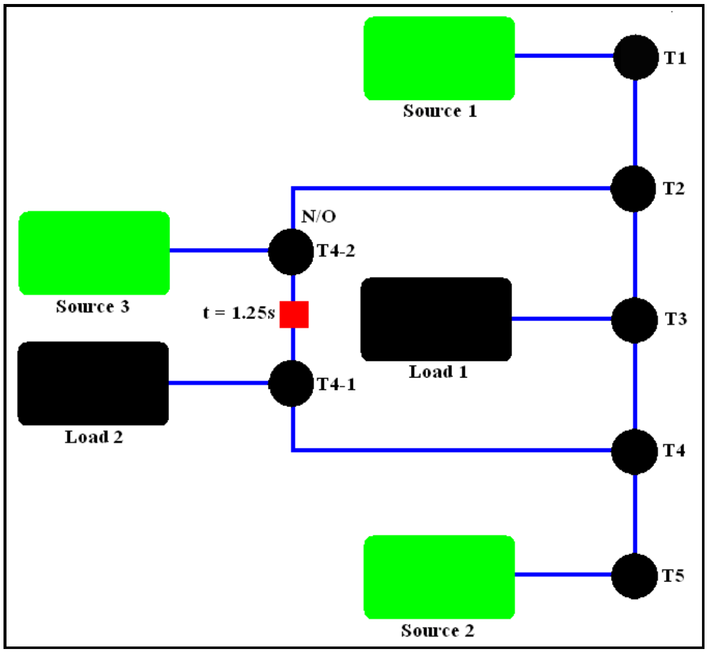

Fig 5.64: Simple representation of the circuit - Example 14 - A fault on a ring connected sub-grid

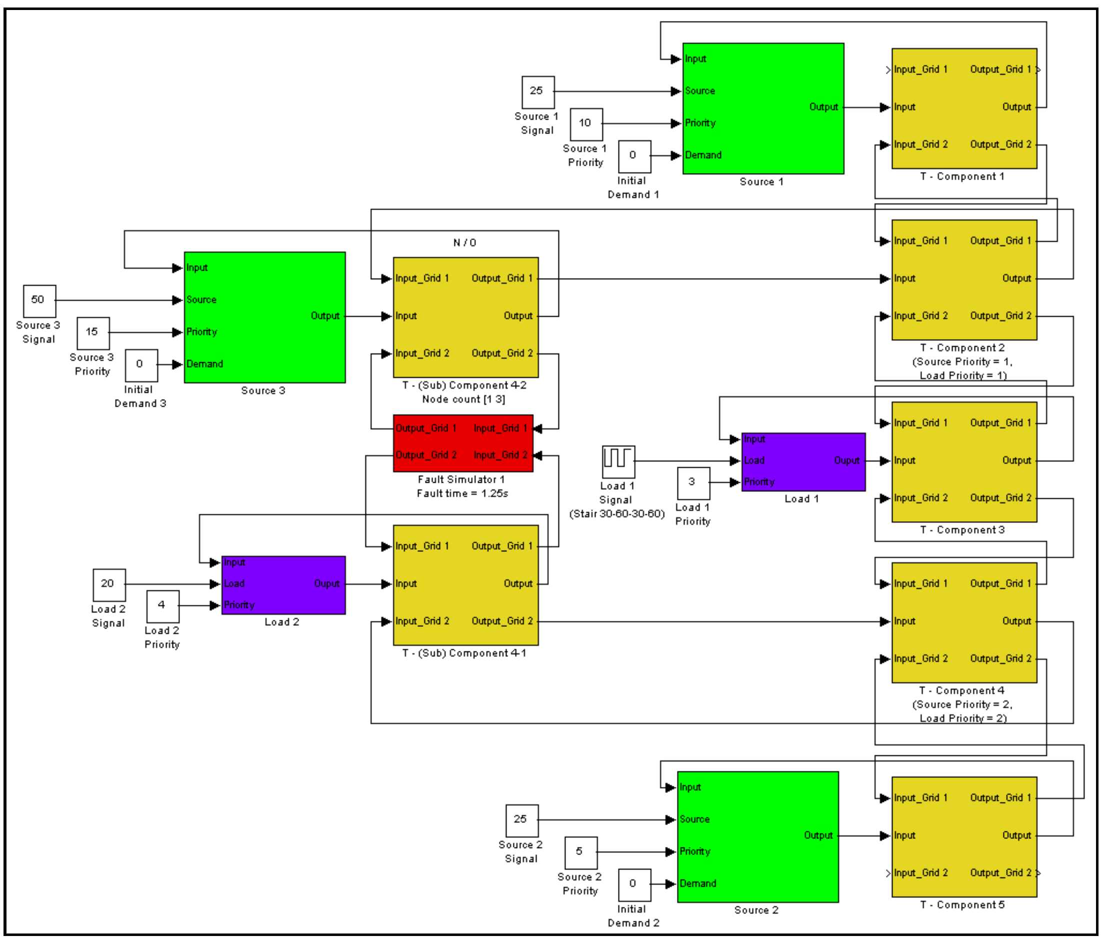

Fig 5.65: Simulink representation of the circuit - Example 14 - A fault on a ring connected sub-grid

In addition, where the sub-grid connects to the main-grid, at 'T4', both the source and load priority is defined as 2 for the sub-grid. However, where the secondary connection of sub-grid connects to the main-grid, at 'T2', both the source and load priority is defined as 1 for the sub-grid. (This allows Grid-operators to have better control over their network and to regulate its connections easily.)

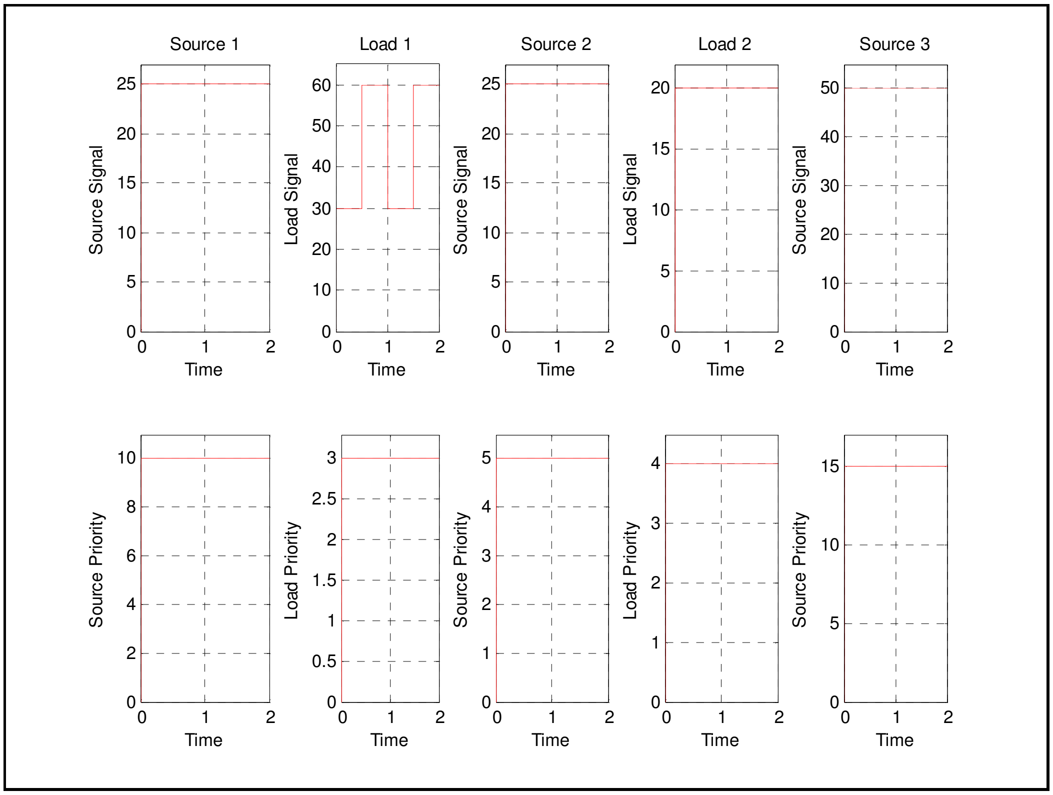

Fig 5.66: Inputs to the circuit - Example 14 - A fault on a ring connected sub-grid

As figure 5.66 indicates; Source 1 can supply 25 units of energy at a supply priority of 10 throughout the simulation. Source 2 can supply 25 units of energy at a supply priority of 5 throughout the simulation. Source 3 can supply 50 units of energy at a supply priority of 15 throughout the simulation. Load 1 has a request of 30 units of energy between 0s and 0.5s and 60 units of energy between 0.5s and 1s at a supply priority of 3. This 1s cycle is repeated for another second in the simulation. Load 2 has a request for 20 units of energy at a supply priority of 4 throughout the simulation.

In the first half of the simulation second for the main-grid, as shown in figure 5.67, Source 1 supplies 25 units of energy at a supply priority of 10, and Source 2 supplies 5 units of energy at a supply priority of 5 to Load 1. (Note that although Source 3 has the highest priority, its interface with the main-grid has the lowest value so it is reduced or shed first.) Thus the supply priority received by the load is 25 / 30 * 10 + 5/30 * 5 = 9.167. The main-grid demand is 30 / (25 + 25) = 0.6.

In the first half of the simulation second for the sub-grid, as shown in figure 5.67, Source 3 supplies 20 units of energy at a supply priority of 15 to Load 2. The sub-grid demand is 20 / 50 = 0.4.

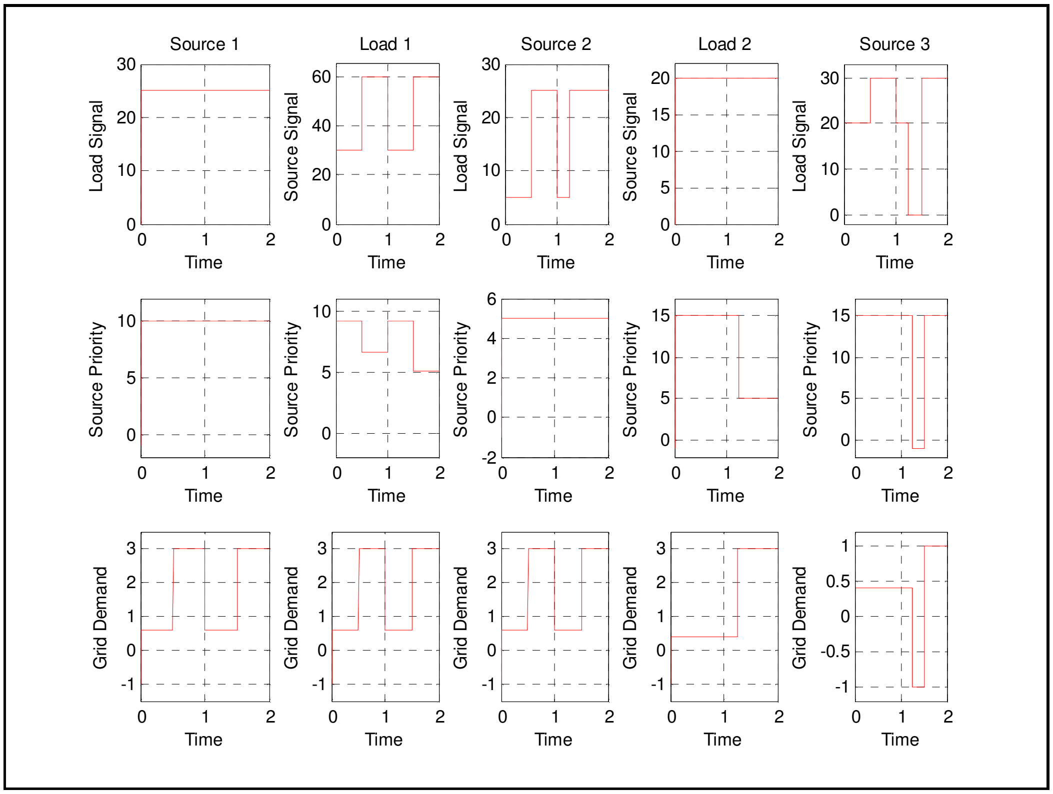

Fig 5.67: Outputs of the circuit - Example 14 - A fault on a ring connected sub-grid

In the simulation period from 0.5s to 1s in the main-grid, as shown in figure 5.67, Source 1 supplies 25 units of energy at a supply priority of 10, and Source 2 supplies 25 units of energy at a supply priority of 5, and Source 3 supplies 10 units of energy through 'T4' at an agreed interface priority of 2 to Load 1. (Note that although Source 3 has the highest priority, its interface with the main-grid has the lowest value so it is reduced or shed first. It thus emulates the value agreed and set between sub-grid and main-grid. Consider Chapter 4 for more information.) Thus the supply priority received by the load is 25 / 60 * 10 + 25 / 60 * 5 + 10 / 60 * 2 = 6.853. The main-grid demand is '3' during this period as its demand exceeds '1', and an intervention occurred to supply Load 1. In this case, the intervention was not load shedding, but energy from an external source which was the sub-grid.

In the simulation period from 0.5s to 1s in the sub-grid, as shown in figure 5.67, Load 2 is supplied at the same priority (because the source stayed the same) and both the source and the load in the sub-grid retains their sub-grid demand value. This is based on the reasoning given earlier that if excess energy is sold to an external grid, which would not have been used by the sub-grid, then it should not impact on the demand of the sub-grid. Should the sub-grid need the energy, then the supply to the main-grid would be shed.

In the simulation period from 1s to 1.25s in the main-grid, as shown in figure 5.67, Source 1 supplies 25 units of energy at a supply priority of 10, and Source 2 supplies 5 units of energy at a supply priority of 5 to Load 1. Thus the supply priority received by the load is 25 / 30 * 10 + 5 / 30 * 5 = 9.167. The main-grid demand is 30 / (25 + 25) = 0.6. (This is exactly the same as in the period 0s to 0.5s.)

In the simulation period from 1s to 1.25s in the sub-grid, as shown in figure 5.67, Source 3 and Load 2 retain their respective priority values and demand values, as nothing has changed in the sub-grid.

At the instance that the simulation time equals 1.25s, the fault simulator is initiated and the connection between 'T4-1' and 'T4-2' is lost. The 'T'-Smart grid recognises the fault as the node count has changed, and closes the N/O point between 'T4-2' and 'T2'. Hence, the grid is solved as if there are a radial main-grid with a sub-grid connected to 'T2' and a sub-grid connected to 'T4'. The sub-grid connected to 'T2' is Source 3 and the sub-grid connected to 'T4' is a Load 2.

In the simulation period from 1.25s to 1.5s in the main-grid, as shown in figure 5.67, Source 1, Source 2 and Load 1 retain their respective priority and demand values as Source 3 has the lowest supply priority value when connected to the main-grid (through the interface that changes the priority values) and would not have been considered at all as an alternative supply point. (It may be that the network between 'T4-2' and 'T2' is old and requires maintenance and Grid-operators did not want to stress this part of the network at all.) The supply to Load 2 through 'T4' would also not have changed the priority and demand values, as explained earlier.

In the simulation period from 1.25s to 1.5s in the first sub-grid connected to 'T2', as shown in figure 9.67, Source 3 is not used or required and hence it is shed. So its priority value and demand value becomes '-1'.

In the simulation period from 1.25s to 1.5s in the second sub-grid connected to 'T4', as shown in figure 5.67, Load 2 is supplied by the main-grid as it has 20 units of extra energy. Source 2 which has the excess energy supplies Load 2 at a priority value of '5'. (It is explained in chapters 4 and Appendix A why this value is retained.) The demand for this sub-grid comprising of only Load 2 is '3' because it is only supplied with what is requested so its demand is '1'. However, the supply comes from an external source (in the case, the main-grid) so the value is incremented to '3' to show that this intervention has occurred.

In the simulation period from 1.5s to 2s in the main-grid, as shown in figure 5.67, Load 2 again increases its load requirement to 60 units of energy which is beyond what the main-grid can supply. Hence, energy is sourced from the first sub-grid through 'T2', at an interface supply priority of '1'. Also, to reduce infrastructure loading, the 'T'-Smart grid will use most of Source 2's energy on Load 2 connected in the sub-grid, and after doing so it will only have 5 units of energy left. Hence, the supply priority to Load 1 is, 25 / 60 * 10 + 5 / 60 * 5 + 30 / 60 * 1 = 5.083. The demand in the main-grid will be '3', as there is no other available energy and Load 1 was supplied by an external source, from the sub-grid connected to 'T2'. (Thus, an intervention occurred.)

In the simulation period from 1.5s to 2s in the first sub-grid connected to 'T2', as shown in figure 5.67, Source 3 now needs to supply 30 units of energy to meet the load request of Load 1. It supplies it at its own supply priority of 15 (prior to the interface with the main-grid) and the demand in the sub-grid emulates the value of the main-grid, as communicated to it, as there is not any loads connected to the sub-grid. (Hence, because it is only a source without any loads to define it as a sub-grid, the main-grid considers it as normal connection to the main-grid without the sub-grid 'T4-2'-component.)

In the simulation period from 1.5s to 2s in the second sub-grid connected to 'T4', as shown in figure 5.67, Load 2 is supplied by Source 2 at a priority of 5 as indicated earlier. Its supply demand remains '3' because it is only supplied with what is requested (thus, the demand is '1') and the energy came from an external source, so the value is incremented to '3' to indicate that this intervention occurred.

Again, it is seen that if a fault occurs and the 'T'-Smart grid closes an N/O to restore supply, then the new solution would differ from the solution prior to the fault. This is because the 'T'-Smart grid always solves the infrastructure limitation problems in an optimal way such as to reduce or kerb future expansion costs on feeders. (This again saves on infrastructure expansion costs, conductor losses and maintenance costs in general.)

5.16 Example 15 - Versatility of the 'T'-Smart grid

It is documented in Appendix A how the 'T'-component communicates in different types of communication vectors when exchanging information between 'T'-components and Grid-components / Sub-grids. In the previous example, the seamless conversion between the communication vectors was proven and this example aims to demonstrate a more complex scenario. Please consult Appendix A for more information on the different types of communication vectors of the 'T'-Smart grid.

In this example, the main-grid supplies a sub-grid which if needed (say, under fault conditions) can connect to the main-grid (i.e. close the N/O) as if the sub-grid and its components were always connected in a radial network to the main-grid and never connected in a sub-grid network formation. As can be expected, the solution differs from before the fault to after the fault event, even though it is the same sources and loads. Consider figures 5.68 to 5.71.

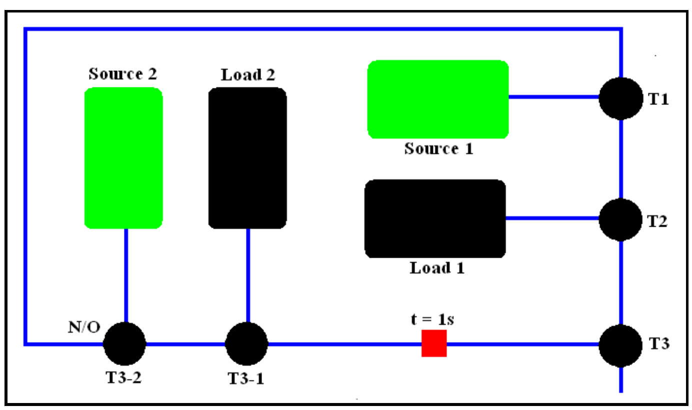

Fig 5.68: Simple representation of the circuit - Example 15 - Versatility of the 'T'-Smart grid

The main-grid comprises of a radial network of three 'T'-components: 'T1','T2' and 'T3'. 'T1' has a source connected to it and 'T2' has a load connected to it. 'T3' is connected to a sub-grid, with two 'T'-components namely 'T3-1' and 'T3-2'. 'T3-1' has a load connected to it, and 'T3-2' has a source connected to it.

When the simulation time reaches 1s, a fault will occur and the network between 'T3' and 'T3-1' will be disconnected. The network will thus close the N/O point between 'T3-2' and 'T1'. (The node count at 'T3-2' is set at 3 nodes above and 2 nodes below, as explained in

Chapter 4.) Then the entire network will be solved as if all the 'T'-components (and Grid-components) are connected in a radial network.

The demand zone of all 'T'-components in this example is set at 2 components above and below for the simulation. There are also no grid (infrastructure) limitations in this example. In addition, where the sub-grid connects to the main-grid, at 'T3', both the source and load priority is defined as 1 for the sub-grid.

As figure 5.70 indicates; Source 1 can supply 50 units of energy at a supply priority of 10 throughout the simulation. Source 2 can supply 50 units of energy at a supply priority of 15 throughout the simulation. Load 1 request 30 units of energy between 0s and 0.5s and 60 units of energy between 0.5s and 1s at a supply priority of 3. This 1s cycle is repeated for another simulation second. Load 2 request 20 units of energy between 0s and 0.25s and 60 units of energy between 0.25s and 0.5s at a supply priority of 4. This 0.5s cycle is repeated for another three cycles, until the end of the simulation. The priority of Load 1 and Load 2 remain constant at 3 and 4 respectively, throughout the simulation.

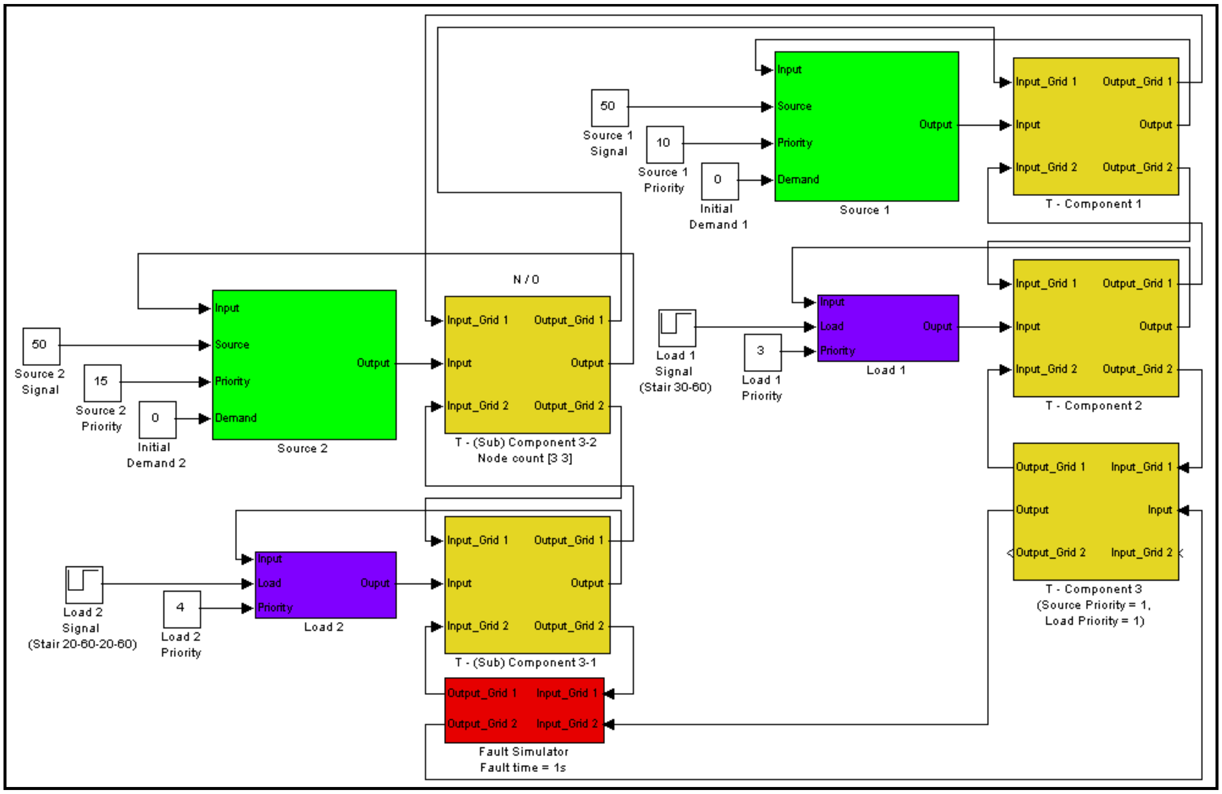

Fig 5.69: Simulink representation of the circuit - Example 15 - Versatility of the 'T'-Smart grid

In the simulation period from 0s to 0.25s in the main-grid, as shown in figure 5.71, Source 1 supplies 30 units of energy at a supply priority of 10 to Load 1. The grid demand in the main-grid is 30 / 50 = 0.6.

In the simulation period from 0s to 0.25s in the sub-grid, as shown in figure 5.71, Source 2 supplies 20 units of energy at a supply priority of 15 to Load 2. The grid demand in the sub-grid is 20 / 50 = 0.4.

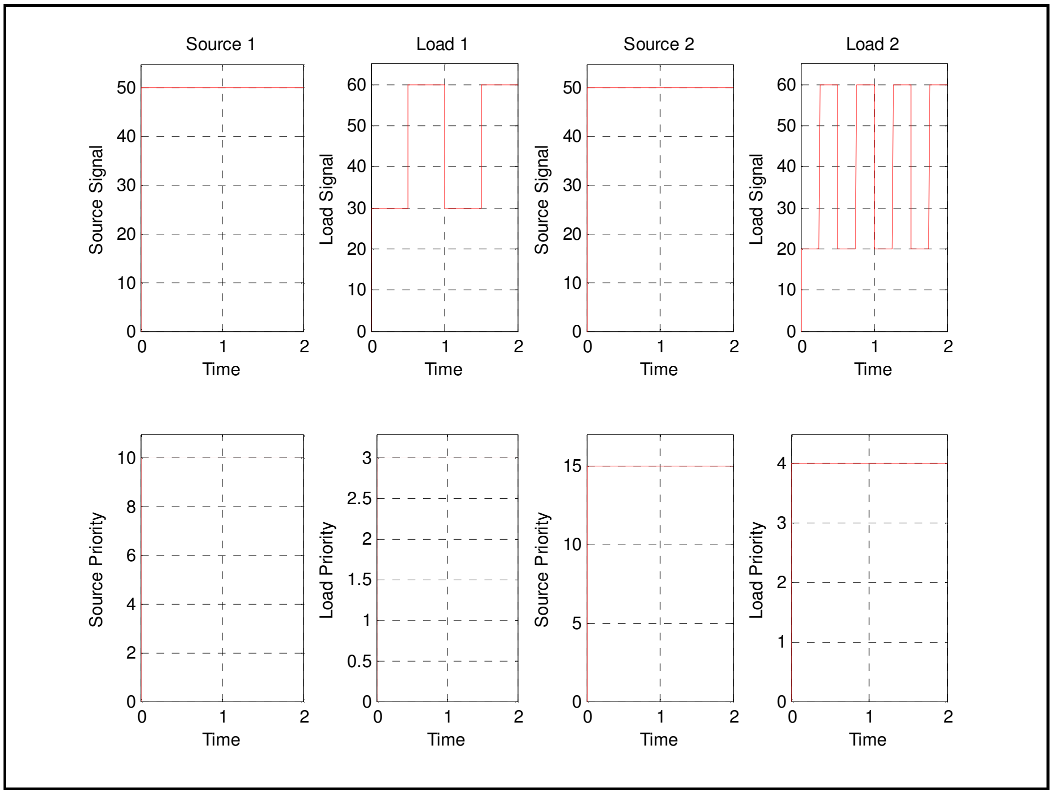

Fig 5.70: Inputs to the circuit - Example 15 - Versatility of the 'T'-Smart grid

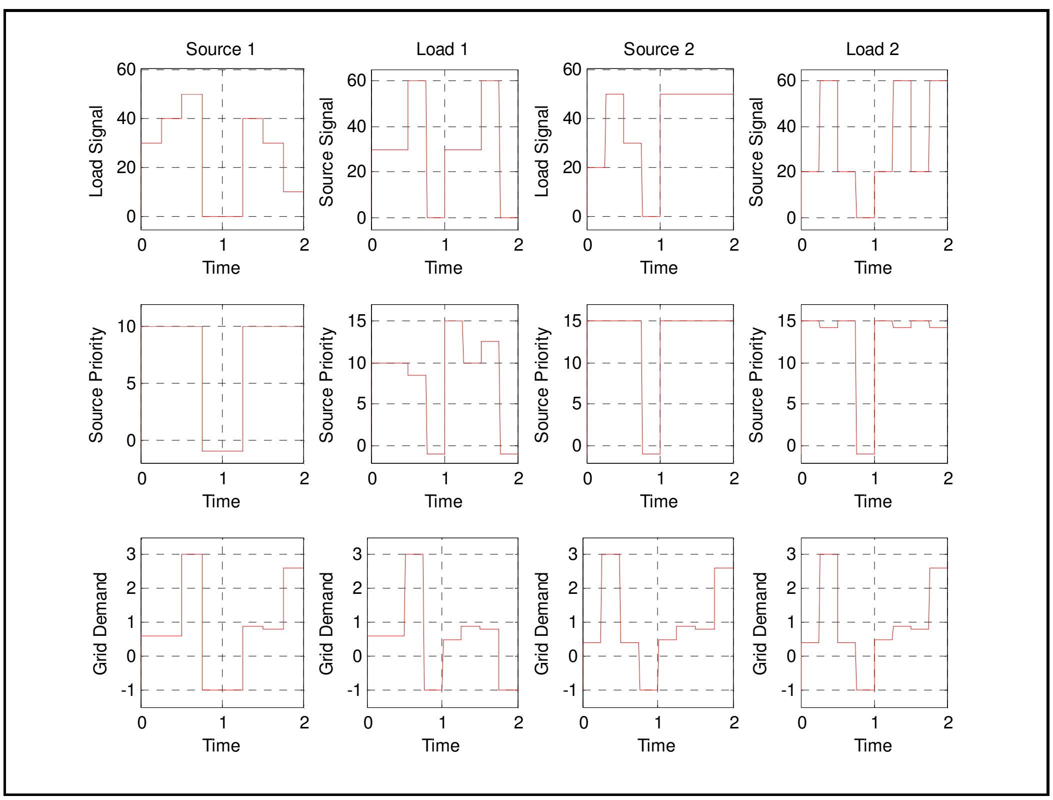

Fig 5.71: Outputs of the circuit - Example 15 - Versatility of the 'T'-Smart grid

In the simulation period from 0.25s to 0.5s in the main-grid, as shown in figure 5.71, Source 1 supplies 30 units of energy at a supply priority of 10 to Load 1. The grid demand in the main-grid is 30 / 50 = 0.6. This is exactly the same as for the period 0s to 0.25s, with the only difference that the main-grid is now also supplying the sub-grid which does not have enough energy to meet the load request of load 2. (Note, as previously mentioned, Load 1 changes its request every 0.5 s while Load 2 changes its request every 0.25s.)

In the simulation period from 0.25s to 0.5s in the sub-grid, as shown in figure 5.71, Source 2 supplies 50 units of energy at a supply priority of 15 to Load 2, but it alone cannot meet the load request of 60 units of energy. So, Source 1 from the main-grid assists with another 10 units of energy at a supply priority of 10. The priority at which Load 2 is supplied at is 50 / 60 * 15 + 10 / 60 * 10 = 14.166. The demand in the sub-grid is '3' because the load request exceeds the local source capability and the Load 2 is supplied by Source 1 from the main-grid (Intervention).

In the simulation period from 0.5s to 0.75s in the main-grid, as shown in figure 5.71, Source 1 supplies 50 units of energy at a supply priority of 10 to Load 1, but it alone cannot meet the load request of 60 units of energy. So, Source 2 from the sub-grid assists with another 10 units of energy at a supply priority of 1. (See grid interface setting in figure 5.69.) The priority at which Load 1 is supplied at is 50 / 60 * 10 + 10 / 60 * 1 = 8.5. The demand in the main-grid is '3' because the load request exceeds the local source capability and the Load 1 is supplied by Source 1 from the sub-grid (Intervention).

In the simulation period from 0.5s to 0.75s in the sub-grid, as shown in figure 5.71, Source 2 supplies 20 units of energy at a supply priority of 15 to Load 2. The grid demand in the sub-grid is 20 / 50 = 0.4.

In the simulation period from 0.75s to 1s in the main-grid, as shown in figure 5.79, Source 1 cannot supply the load request of Load 1, and the sub-grid can also not assist as it also has insufficient supply to meet its local load request. Hence, Source 1 and Load 1 are shed and their respective priority and demand values become '-1'.

In the simulation period from 0.75s to 1s in the sub-grid, as shown in figure 5.71, Source 2 cannot supply the load request of Load 2, and the main-grid can also not assist as it also has insufficient supply to meet its local load request. Hence, Source 2 and Load 2 are shed and their respective priority and demand values become '-1'. (Note that all the loads were shed due to incorrect network configuration or due to incorrect settings of the sub-grid's priority. This could have been avoided by setting the priority values differently which would at least ensure that one Load can be supplied.)

When the simulation reaches the 1s period in the simulation time, a fault occurs between 'T3' and 'T3-1' and this part of the circuit is disconnected. Furthermore, 'T3-2' senses that the node count has changed and thus closes it N/O between 'T3-2' and 'T1'. Thus, the network is now solved as if connected in a single long radial network.

In the simulation period from 1s to 1.25s in the new main-grid (comprising of four 'T'-components in a radial connected network), as shown in figure 5.71, Source 1 can supply the load request of Load 1 and Load 2 at a supply priority of 15. The grid demand in the new main-grid is (30 + 20) / (50 + 50) = 0.5. (Note that Source 2 has a '-1' priority and demand value as it is shed because it is not used.)

In the simulation period from 1.25s to 1.5s in the new main-grid as shown in figure 5.71, Source 1 and Source 2 can supply the load request of Load 2 at a supply priority of 50 / 60 * 15 + 10 / 60 * 10 = 14.166. Note that Source 2 is the highest priority source and Load 2 is the highest priority load in the new main-grid. Thus, the energy of Source 2 is used first and then the energy of Source 1 is added to meet the load request of Load 2. After supplying Load 2, Source 2 has no energy left and hence Source 1 supplies Load 1 on its own at a priority of 10. The grid demand in the new main-grid is (30 + 60) / (50 + 50) = 0.9.

In the simulation period from 1.5s to 1.75s in the new main-grid as shown in figure 5.71, Source 1 and Source 2 can supply the load request of Load 1 at a supply priority of 30 / 60 * 10 + 30 / 60 * 15 = 12.5. This is because Source 1 is a lower priority source and thus its supply is reduced first. So, Source 2 (which is a higher priority source) supplies 20 units of energy to Load 2 and then its reminder of energy is added to Source 1's energy to supply Load 1. The supply priority of Load 2 is 15. The grid demand in the new main-grid is (60 + 20) / (50 + 50) = 0.8.

In the final simulation period from 1.75s to 2s in the new main-grid as shown in figure 5.71, the combined load request of Load 1 and Load 2 exceeds the combined energy capacity of Source 1 and Source 2. Hence the lowest priority load, Load 1 is shed and its priority and demand value is '-1. Source 1 and Source 2 then supplies Load 2 at a priority of 50 / 60 * 15 + 10 / 60 * 10 = 14.166. The grid demand in the new main-grid is (60) / (50 + 50) = 0.6. However, this value is incremented by '2', to indicate that an intervention, in the form of load shedding (Load 1) has occurred.

This example shows the versatility of the 'T"-Smart grid to seamlessly reconfigure and solve itself in a new network configuration without the need for any external influence. The reader should also note the different solutions obtained from the same sources and loads, in two different network configurations, which emphasises the need for Grid-operators to carefully consider network configurations before implementation. Also, from knowledge of Appendix A, the reader would note that this occurred due to the seamless conversion between different communication vectors the 'T'-Smart grid makes use of.

5.17 CONCLUSION

This chapter aimed at showing how the 'T'-Smart grid would operate under different grid constraints and what the final outcome would be under these conditions. In all cases, the agility and robust decisions of the 'T'-Smart grid makes it an important platform to measure other Smart grid proposals from, and it addresses the problem statements and objectives mentioned in Chapter 1. (See Chapter 6 for more details.)

Example 1 - A source and a Load, showed that sources can supply loads in the absence of a 'T'-Smart grid as expected. In Examples 2 - Sources only and Example 3 - Loads only, it was shown that if only sources or loads were present, the 'T'-Smart grid and grid in general, would not be necessary but it would remain stable until a different Grid-component was connected.

In Example 4 - Three sources and a load, it was shown how the Control-component can alter the priority values of Grid-components, to have the 'T'-Smart grid solves itself in a different but also predictable manner to a state which the Grid-operators require. In addition, it was also shown how the internal demand of a source (supplying additional non-grid loads of its owner) was taken into consideration by the grid, and how the owner can still have access to the source's actual supplied energy to determine maintenance schedules form it.

Example 5 - Sub-grids, Demand zones and Interventions illustrated in practise a powerful technique that can be used by Grid-operators to charge customers for the specific shared network they used to supply their loads and for grid events (if required). This was determined through demand zones and interventions (explained in Chapter 4) and this was also considered for a sub-grid. Thus, through correct settings of the demand zones, and whether to charge for interventions or not, Grid-operators are in a position to predict how the grid would solve itself for a given set of minimum to extreme loading patters, and based on this ensure the grid solves itself in the manner they choose.

Example 6 - Increased demand due to infrastructure constraints, demonstrated how the 'T'-Smart grid can take into consideration capacity limitations of the grid feeders, the internal busbar of the 'T'-component, and its grid connection ports. (This includes limitations of the FCL as well.) It also showed how it would adapt the grid demand, to both alert customers of the limitation but also in doing so, charge customer extra (due to the increased demand) for using the constrained grid element. The funds obtained from the increased demand can later be used towards a project to correct the constraint, if necessary and if it agrees with the long term expansion plan of the grid. Example 7 - Dividing energy in a constrained network, was a follow up example to further show that the 'T'-Smart grid determines its grid limitation intelligently and allows double the amount of the perceived capacity limitation through it, if loads are split equally and to its maximum (FCL) value to both sides of it. It was also shown that that the busbar limit was not exceeded at any time.

The four examples that followed (Example 8 to Example11) demonstrated the different ways in which the energy storage element could operate. In Example 8 - Energy storage element's first mode of operation, the energy storage element only stored energy which the grid didn't use and so increased the source's supply capacity. During this time it was emulating the source and acting as an extension of it.

In Example 9 - Energy storage element's second mode of operation, the energy storage element studied and predicted the customer's loading habits to ensure an almost flat energy profile is always requested from the grid. (This then limits peak demand that later lead to unwanted infrastructure upgrades.) During this time it was emulating a load and acting as an intelligent management extension of it.

Example 10 - Energy storage element's third mode of operation, showed how it would act intelligently and always store extra energy from the grid, and then later discharged it when the supply couldn't be met without it. The most important aspect of this operation was the fact that it didn't impact on the demand of the grid when it stored energy, as this energy would have been lost if not used (consider Chapter 4 for more information). This powerful decision (which is considered a fundamental step in solving the energy demand problem) grows the source capacity base of all the sources connected to the grid and dramatically assists with peaking load. (It was also shown to have the ability to vary several internal control parameters to charge energy from a sinusoidal input energy signal.)

In Example 11 - Energy storage element in a sub-grid, another important aspect of the energy storage element's properties was demonstrated. It was connected to a sub-grid and it then only ensured that excess energy from this sub-grid (and sub-grids connected to it) is stored and discharged when necessary. This then prevents unwanted energy flow between the main-grid and sub-grid which could later lead to infrastructure upgrades which is not necessary and can be expensive in comparison to having sufficient local sources connected to the sub-grids. Customers could also then benefit from it, as if they own the sub-grids, and it might be preferable to store energy generated by themselves (at a reduced cost and increased reliability) and use it as needed, rather than to sell it to the grid to only purchase it back later a possible higher price. (Only excess energy from the sub-grids, generated by sources after the energy storage element reached saturation or maximum charging capacity, would be sold to a higher grid or the main-grid.)

Example 12 - A fault on a radial network, showed two main-grids that were solved independently (both radial networks) and then together, after a fault occurred and a segment of the energy generating part of the grid was lost. Thus, the 'T'-Smart grid could adapt to a fault in the network automatically (based on its proposed node count protection explained in Chapter 4, or other means) and connect the radial networks together with no supply loss to the Loads, due to the FCL system used (also explained din Chapter 4).

Example 13 - A fault on a ring network, then further explored this when considering a ring type network that was solved in a radial way (assuming the closing side connection was far away, has high energy losses and the maintenance on it is expensive) and after a network fault occurred, it immediately used the back-up supply connection to again ensure an uninterrupted fully radially connected supply. The outcome of the simulation then further showed that apart from the supply parameters (priority values and demand values) that differed due to the re-configuration of the network, the 'T'-Smart grid always solved itself (as first most important priority) in an optimal way such that the minimum amount of energy is transferred across a given medium to again save on infrastructure expansion costs, conductor losses and maintenance costs in general.

Example 14 - A fault on a ring connected sub-grid, followed on the demonstration of the automatic switching capabilities of the 'T'-component (from Example 13) and further showed how the sub-grids can be solved under different circumstances, but also, how a main-grid can be used to transfer energy from one sub-grid to another and so ensure that always the minimum amount of Loads are shed. Also as with the previous example, it was shown that the infrastructure usage was optimised such that the 'T'-component (Smart grid) would always avoid unnecessary future expansion / upgrades of feeders and the grid in general.

Finally, in Example 15 - Versatility of the 'T'-Smart grid, it was shown how a previously connected sub-grid was re-connected to a main-grid in a radial connection, and not as a sub-grid. This just showed the compatibility and versatility between connection ports of the 'T'-component and the seamless conversion between communication vectors explained in Appendix A. Also, this example highlighted the effect of configuring the network incorrectly or setting the priority values of the sub-grids incorrectly, as in such cases the network would respond in an undesirable manner. However, due to the nature of the 'T'-Smart grid and its properties, Grid-operators can plan and predict the problem in a simulated environment and take the necessary actions prior to implementation.

These properties and means to solve the grid are considered the minimum performance of future designed and implemented Smart grids and assists in showing how the 'T'-Smart grid can meet the requirements of Chapter 1.

CHAPTER 6: CONCLUSION AND FUTURE WORK

As the demand for electricity increases worldwide on usually constrained networks, many factors prevent the implementation of conventional generation as a solution. Smart grids offer alternative solutions that would be integrated into the existing electrical infrastructure to limit or lessen peak demand and two common models have already been used worldwide: to charge customers a peak tariff in peak loading time (through the use of Smart meters, to motivate customers to reduced or move their load usage) or, to store (and even physically move) energy in off-peak time which can later be used in on-peak time. (Chapter 1)

However, these proposals did not fully address the demand problem, the current trend of centralised generation (which require networks to transport the energy), or the required communication and participation aspects between users and the utility as detailed in [1]. The American DOE tabled these three important aspects in addition to several other capabilities, properties, technologies and techniques the future Smart grid should have. (Chapter 1)

The problem statement of this dissertation was then to develop a Smart grid system, one which presents possible solutions to these three constraints. Hence, it would ensure fully protected, seamless, demand lowering integration between distributed sources, loads and energy storage systems. (Chapter 1)

In future, several distributed renewable and non-renewable energy generation technologies are expected to be intelligently integrated into the grid, with or without energy storage capabilities that would greatly assist in lowering grid demand. (Chapter 2)

Other Smart grid proposals to lower peak demand includes the integration of widely recognized DMS systems, which still needs to be adapted to effectively operate in future Smart grids. (This is due to unpredictable high and low peak demands periods that may be created by other Smart grid solutions, customers reacting to price incentives, devices / system with objectives not aligned to that of the grid's, etc.) ADMS solutions are now being proposed to achieve the same results as the DMS solutions in an environment where load predictions are complex and the forecasting functions take several external factors into consideration. (Chapter 2)

Using distributed renewable and non-renewable generation, energy storage devices, and making use of DMS and ADMS solutions to assist in lowering peak demand does not realise the reliability and customer requirements of future Smart grids as described in [1]. (Chapter 2)

Thus, as part of the dissertation, at least two solutions currently being proposed by industry were briefly discussed. (Chapter 2)

The first solution made use of Local Controllers to manage responsive loads, distributed resources and energy storage in local portions of the power grid. It was then shown that through various information interfaces, collection of data and processing and logical decision making, it could meet the customer expectations, preferences, system reliability and power quality as mentioned in [1]. (Chapter 2)

The second solution was based on an Energy Internet whereby energy was virtually stored (at least partially) without the need for energy storage elements. This ensured a reduction in peak demand and an increase in grid stability by scheduling electricity usage of customers in advance. This could only be achieved if information is intelligently managed and shared, a clearly defined model is used for price elasticity in order to manage uncertainty, smart meters equipped with bidirectional communication capabilities is used, the electricity consumption could be accurately forecasted, and multi-resolution agents cooperating with one another are present that would act on behalf of the customers, grids and other parties. (Chapter 2)

The 'T'-Smart grid is a proposed solution which seamlessly and intelligently integrates distributed resources and energy storage devices and can act as a platform from which the DMS and ADMS functions can be effortlessly integrated, interfaced and managed. Key concepts from the proposed Local Controller and Energy Internet solutions are also used to further create the proposed 'T'-Smart grid solution. (Chapter 2 to Chapter 4)

The novel 'T'-Smart comprises of a Control-component, 'T'-components and Grid-components (sources, loads and energy storage elements.) of which the Control-component and 'T'-components form the fundamental components of the 'T'-Smart grid solution. This novel solution is an interim to end-state network transition solution where it is assumed that the future grid would only comprise of islanded loads and sources connected together by small grids while the main-grid will only be used as a back-up supply. Hence, if loads have nearby sources, a main-grid may not be required. This assumed end-state of the grid will only be realised once compact energy generation and energy storage technologies are fully developed. (Chapter 3 and Chapter 4)

The Control-component is similar to the existing SCADA but is fully automated and does not manage day-to-day grid operations. Instead, it only collects data from the 'T'-components and performs several off-line functions and can perform overriding functions such as re-configuration of the grid, emergency switching, identifying upgrades (based on load forecasts), determining equipment to be maintained (based on age and previous overloading), controlling and monitoring feeder overloading, electrical isolating functions (where the 'T'-component fails) and the transmission of real-time grid information to customers and billing in general. (Chapter 3)

The 'T'-components acts as a local controller and manages all day-to-day grid functions. It manages interfaces with other 'T'-components, Grid-components, sub-grids and customer devices and is responsible for the general management of energy transfer and distribution in the grid. (Chapter 3)

Physically, the 'T'-component is a three port energy transfer component of which two ports interfaces with the main-grid and the third port (which can be an input or output) interfaces with sources, loads, energy storage elements (Grid-components) and sub-grids. Any port can either be an input or output, depending on grid conditions. (Chapter 4)

The 'T'-component of the proposed 'T'-Smart grid has many important properties of which the most important is to (Chapter 4):

- ✓ Ensure seamless integration between, and management of, an unlimited number of Grid-components (sources, loads and energy storage elements) in the main-grid and sub-grids such that network capacity constraints and peak loading will be minimized and,

- ✓ Ensure complete electrical protection between all Grid-components and sub-grids by eliminating the propagation of fault currents and limiting fault current amplitudes (to reduce associated infrastructure fault capacity upgrades and earthing requirements).

The above two properties are achieved through the implementation of a novel Fault Current Limiter (FCL) inside the 'T'-component that temporarily charges energy from the grid and discharges energy to the grid, in a small internal fast switching temporary energy storage device. This enables the 'T'-component to limit fault current amplitude and propagation throughout the grid as the fault current amplitude / energy is limited to the small storage device's capacity. The FCL system also enables the 'T'-component to emulate different output voltage signals (as required by the grid) and the rate at which the FCL discharges can be used to detect faults in the grid in order to automatically close N/O points in the network, if available. (Chapter 4)

Because energy first needs to be stored inside an FCL, before it can be discharged, it creates a grid with discrete grid states (similar to a sampler in an analogue to digital converter). These grid states created by the FCL allows the 'T'-Smart grid the opportunity to adequately and predictably assess, manage and control any network condition without interruptions to the customers (through a control process) and to optimally solve the grid's next state, as all the available energy and load requests are known upfront. (Chapter 4)

The 'T'-components also manages sub-grids such that only the minimum amount of energy from the main-grid is used to assist a sub-grid and vice versa. This leads to sub-grids that will always first utilise its own energy sources and storage elements before considering the main-grid. This then reduces the need for a main-grid and creates many small distributed sub-grids with their own energy sources and storage elements which the 'T'-Smart grid is designed for. Furthermore, it is anticipated that a large number of small energy storage elements (at customer level) will be easier to implement than strategically placed larger storage elements and will have a greater impact on reducing peak demand. Once distributed energy storage elements are installed closer to the loads, it will greatly assist in the reducing the need for network expansions and upgrades. (Chapter 4)

The 'T'-component manages the grid and ensures loads are supplied by sources based on a priority system determined by the Grid-operators. (These priority values can be based on many factors including environmental considerations.) In this system, the highest priority source supplies the highest priority load first. However, the 'T'-component can deviate from this rule, to realise a more optimum grid solution, if some grid elements are constrained / limited as seen in Chapter 5. Similarly, Energy storage elements and sub-grids are assigned priority values in order for the 'T'-Smart grid to solve the network from a highest priority to a lowest priority Grid-component. Grid-operators, through the use of the Control-component, can also change any priority value (at any stage) of sources, loads and energy storage elements, together with demand charges, zone network charges and intervention (use of external grid, or shedding of another load) costs, as described next, to optimally and efficiently manage and control the grid according to their preference. (The eight step control process used to solve the grid and control the energy added, released and distributed in the grid according to priority and other factors are described in Chapter 4.) (Chapter 3 and Chapter 4)

As a means to manage peak demand, Grid-operators can assign unimportant loads a low priority value such that it would be shed first if there is insufficient energy available in the grid. Due to the way that 'T'-Smart grid is set up, load priory values are not unique and a number of unimportant loads can be grouped together under a common priority value so that if load shedding occurs, load groups (in an area) instead of peaking load areas / networks are shed. (Chapter 4)

Another set of techniques to reduce peak demand and the need for infrastructure upgrade includes:

- ✓ Billing loads and energy storage elements in charging mode a demand zone charge which is an accurate shared network charge calculated in real time based on the exact network used at that time (for a specific load) to transport energy from a source(s) to the load. This should motivate customers to consider more local energy sources and energy storage elements rather than to prolong the use of the main-grid. (Chapter 4)

- ✓ Notifying Grid-components that an intervention occurred. An intervention has occurred when load was shed to supply another load or when energy was acquired from an external grid. (Note that sources and energy storage elements in discharging mode are also notified, so that they can be rewarded for supplying energy during this time, if Grid-operators require this function.) (Chapter 4)

- ✓ Taking into consideration network capacity constraints and increasing the demand accordingly, as the energy transfer is constrained and the available energy reduced (due to the network limitations). This increased demand is communicated to all Grid-components and funds generated from this increased network demand can be used to upgrade constrained elements (if it forms part of the grid's long term plan). (Chapter 4)

Another strategy the can be implemented by the 'T'-Smart is to not necessarily reduce the amount of energy used, but to reduce the peak demand to a flatter average energy consumption profile by providing financial incentives to customers making use of distributed energy storage elements and renewable sources, closer to the loads based on the three previous or other techniques. Those customers consuming a flatter energy profile (and not necessarily a reduced average energy profile) will benefit from this system the most.

Both the financial incentive and physical hardware solutions such as energy storage elements would reduce the peak demand and it can be decided to first introduce benefits to customers making use of energy storage devices, and later to those implementing renewable sources. It would then be the responsibility of the Control-component to issue customers with credit / debit accounts considering the source's / load's / energy storage element's, assigned priority values, demand values (taking into consideration the above three charges), duration of connection, and energy quantities supplied / used, etc. for demand control but also to promote and establish a platform for a future energy trading market and better communication between the customer and the utility. Grid-operators will then determine the weight of each factor in order to effectively manage and control their grids.

The 'T'-Smart grid has the ability to control a large number of Grid-components especially sources and energy storage elements that would assist in reducing the peak demand which will then kerb the need for infrastructure upgrades, and a fully capacitated main-grid. Hence, the grid does not directly profit from these incentives, but because of the significant reduction in network expansion and possible maintenance costs due to this, benefits over the long term. (Chapter 4)

The energy storage elements implemented in the 'T'-Smart grid (hardware solution) as a solution to reduce peak demand can intelligently interact with the 'T'-components and other Grid-components and can operate in three important modes of operation:

- ✓ In first Mode of operation, the energy storage element is connected in series between a source and a 'T'-component. The object is to store excess energy not used by the grid and effectively increase the source's supply capacity. (Chapter 4)

- ✓ When in the second mode of operation, the energy storage element is connected in series between a load and a 'T'-component. The purpose of the energy storage element is to draw a constant energy profile from the grid, while the load connected to it varies unpredictably in supply requirements. (Chapter 4)

- ✓ If the energy storage element is connected to the grid / sub-grid / sub-sub-grid alone, it can function in its third mode of operation. The purpose is to store excess energy (after other energy storage elements functioning in the first mode of operation are saturated) and to later discharge the excess energy (after other energy storage elements functioning in the second mode of operation have fully discharged), in the grid. (Chapter 4)

In order to display the 'T'-Smart grid's ability and agility to make robust decisions in complicated yet common situations which a future Smart grid would need to solve, fifteen different examples were discussed using simulated 'T'-components and Grid-components. It was shown:

- ✓ that the grid can maintain stability,
- ✓ the Control-component can change priority values of Grid-components and how this would affect the grid's solved state,
- ✓ how customers are accurately charged for SNCs and interventions,
- ✓ the ability of the 'T'-components to take into consideration grid and feeder limitations (including FCL limitations) as well as how it increases the network demand accordingly,
- ✓ how the energy storage element can be utilised in three different modes of operation, each with its own unique benefits, with the third mode being most preferable to customers who want to store their generated energy and maintain their own networks rather than selling it to the grid and,
- ✓ the 'T'-Smart grid's capability to solve different radial, ring-type, sub-grid and other grid-configurations in case of a fault to ensure the maximum number of customers retain supply.

Throughout most of the examples it was clearly shown that the 'T'-Smart grid first considers network constraints before energy constraints, to ensure the minimum network elements are overloaded (in worst-case scenarios) and thus to prevent unnecessary infrastructure upgrades when a different network configuration could solve the problem. (Chapter 5)

It should be noted that the simulated 'T'-Smart grid-component models all have fixed states with a fixed set of instructions to follow which lead to a fixed and predictable outcome.

These instructions sets, of all the Grid-components, in terms of their priority values and other rules, get executed only once per grid state to ensure the 'T'-Smart grid is stable. However, it cannot be proven that optimal states will always be reached where the worst case is that all Grid-components are simply disconnected.

In conclusion, it was shown that through the use of numerous distributed sources and energy storage elements (operating in three different modes of operation), seamlessly integrated with distributed loads through an FCL switching system, managed correctly, using charges and incentives to kerb infrastructure expansion and upgrades, and by supplying customers with all the required grid information, the 'T'-component of the 'T'-Smart grid address the problem statement described in Chapter 1 which was to:

- ✓ To reduce peak demand,
- ✓ Ensure sources, loads and energy storage elements can be integrated seamlessly and to,
- ✓ Promote a platform for improved interaction between the utility and the customers.

Therefore, the 'T'-Smart grid, its components, properties, grid management rules, models and test simulations results are considered not only a possible solution but also the minimum performance of future Smart grids and an important model to measure other Smart grids from.

FUTURE WORK

Future work in general for all Smart grids may include the design, testing, development and implementation of the following:

1) A physical device that can accurately 'learn' loading behaviour of residential customers, 'learn' the availability of renewable sources and other sources of energy that are not constant, and advise the customer on the size of the energy storage element required. In addition it must also manage this energy storage element such that it would draw a constant energy stream when non-renewable base-load sources are used (to avoid peak demand) and to draw energy at a higher rate (while sharing this energy with other storage elements and loads) when renewable energy is available. (Also, it must have the physical properties to charge and discharge energy efficiently at both a high rate and lower rate.)

   This function will require an advance built-in artificial intelligent system which can later be extended into a powerful energy management system that can control the customer's sub-grid (Smart Home for example) and also act as a 'trader / negotiator' on behalf of the customer, when electricity is procured or sold in an energy trading market. This function will then further assist in reducing the grid's peak demand by integrating predictive intelligence and logical pre-determined (set-up) decisions with a smart metering system, to take several factors into consideration in addition to what is predicted, so that an optimal outcome for both the grid and the customer can be reached.

2) Once 1.) above is achieved, this device must be extended to not only manage loads of a single residential customer, but loads and energy flow throughout a grid as

described by the Third operation mode of energy storage elements. This device must not only minimize the flow of energy throughout the grid (in peak time, which leads to unwanted network upgrades) but it must interact with other storage devices as well to ensure the maximum amount of energy is always stored in the most optimal points in the grid, to ensure the maximum amount of renewable energy is always used or stored while minimizing the need for non-renewable (base-load) energy.

3) A sub-system in the future grid that can manage energy sources and storage elements of the same priority, by drawing different amounts of energy from each but still ensure that the demand experienced by each is equal, before taking network infrastructure constraints into consideration. Then, if a given source is closer to a load centre and using this source would reduce the need for future network expansion, to use this source and then to 'lock' this decision into the future grid's solving method. (Voltage profiles should also be taken into account.)

   The problem that is avoided by assigning unique priority values to energy sources and energy storage elements in the 'T'-Smart grid is that if there was a load which was supplied by two sources (with equal priority) then the source with the lowest demand may be chosen if not other parameters (for example network length, network loading, energy flows, volt drop, etc.) influenced the decision.

   However, once it draws energy from that source, the source's demand suddenly peaks and at the next grid state the same algorithm might not choose the same source again (depending on load size) as its demand may now be higher, because of the load connected to it. Instead, it would choose the other source which in the previous grid state had a lower demand as it is not burdened with the load which had just been connected to the grid.

   Hence, the other source is now chosen to supply the load, and after another grid state change, the same algorithm determines that the previous source be used again. This leads to rapid and unnecessary switching between 'T'-components and sources which can later lead to network instability and even malfunction. Drawing energy from both sources such that both source's demand is equal after supplying the load is not a solution on its own, as the Grid-components' requirements will change constantly which means that this calculation and the network switching associated with this will also have to change continuously. The only solution will be to define a set of logical conditions which will guide which source will be used and how, and then to 'fix' this decision into the solving method of the grid.

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APPENDIX A: 'T'-SMART GRID SIMULATION MODELS

A.1 INTRODUCTION

In Chapter 3 and Chapter 4 the requirements, properties and fundamental behaviour for the 'T'-components were described. In this chapter, the 'T'-component and all other Grid-components are modelled in a simulation environment. A high level model description of the internal workings will be given, together with actual models used for testing and analysis in Chapter 5.

A.2 COMPARISON BETWEEN THE PROPOSED INTERNAL CONSTRUCTION AND SIMULINK MODEL

In the Chapter 4, a high-level physical internal layout was given as to how the hardware inside the 'T'-component should be arranged to achieve its physical properties and Smart grid requirements. This appendix focuses more on the software from a high-level down to a detailed-level regarding its internal workings to achieve the same objectives.

The (Matlab) Simulink representation of the 'T'-component, a source, load and energy storage element will follow in figures A.1 to A.4.

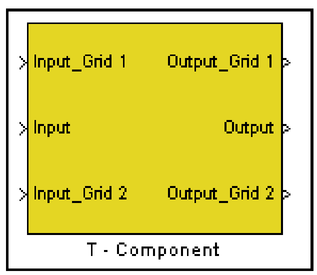

Fig A.1: Simulink representation of a 'T'-component

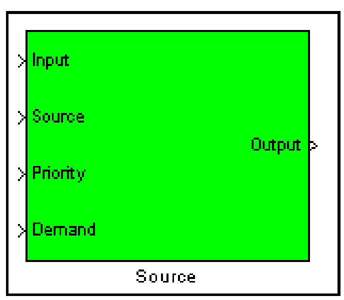

Fig A.2: Simulink representation of a Source

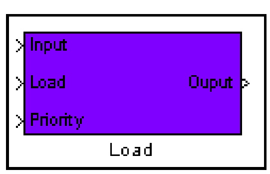

Fig A.3: Simulink representation of a Load

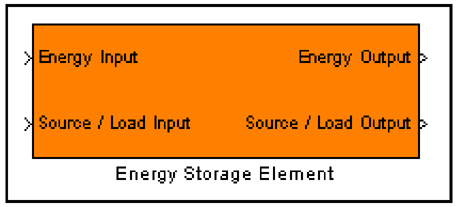

Fig A.4: Simulink representation of an Energy Storage Element

Note that the Control-component is not modelled because the 'T'-Smart grid needs to function autonomously as tested in Chapter 5. The Control-component is only used to override the system and testing this will have no benefit in analysing the 'T'-Smart grid, in a simulation environment.

A.3 DATA COMMUNICATION BETWEEN 'T'-COMPONENTS

A fundamental part of any Smart grid is its means to effectively communicate. As described in [1], future Smart grids will require advance and very reliable communication to realise the functions and applications mentioned in Chapter 1 and Chapter 2.

Thus, some investment in telecommunication for the future Smart grid is required. However, in order to ensure that it is as cost effective as possible, the communication protocol needs to be very efficient with the least amount of data being sent and received between Grid-components before action is taken.

Below is a proposal for such a protocol, with specific reference to the required information to be sent and received in order for the system to function. This system was then also implemented for the 'T'-Smart grid (simulated in Chapter 5).

Each 'T'-component sends five pieces of information to its neighbouring 'T'-components left and right from it. This information is sent by Port 1 and Port 2, labelled 'Input/Output Grid 1' and 'Input/Output Grid 2' in figure A.1. The information is sent in a communication vector and contains the following parameters:

[Signal value, Priority, Energy Total, Load Total, Counter] (A)

In the sections to follow, each parameter will be discussed in-depth in order to describe how the system manages to function from this limited number of parameters.

Note that energy is supplied, transported and consumed at each increment of time throughout the 'T'-Smart grid. Therefore, because energy is supplied or consumed per a time interval, one can view it as apparent or real power being generated or used. (The 'T'-Smart grid will only distribute power factor corrected signals so the apparent power equals the real power.) However, for explanation purposes, the term energy will be used as in a given time increment, we would be accounting for the available energy in the grid being generated, distributed or used.

A.3.1 SIGNAL VALUE

The signal value at any instance in the grid can be positive or negative and is a mathematical sum of the available energy or shortfall of energy in the grid. (i.e. Sources as assigned a positive number and loads a negative number.)

For example, consider the figure below showing two loads with their energy requirements and one source with a priority of '1' and its available energy of '50' units.

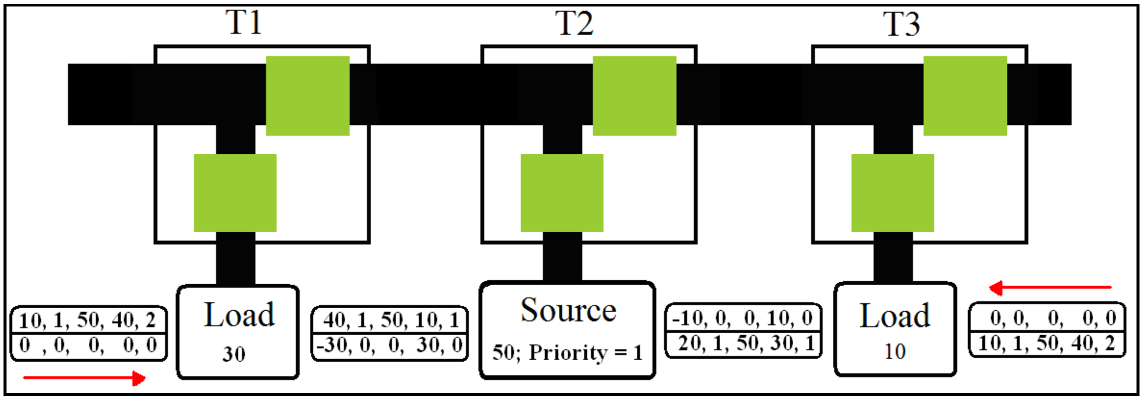

Fig A.5: Communication representation between 'T'-components

Consider the lower and upper row of numbers (at each 'T'-component) which represent the information of the communication vector given in (A). This communication vector flows from left to right and right to left, as information is send to the left and right of each 'T'-component, as indicated earlier.

Now focus on the lower row of number, on the far left: '0,0,0,0,0'. After the first load (load connected to 'T'-component 1), the Signal value (first value in the communication vector) is decreased by 30 as loads are assigned negative values. (i.e. The communication vector changed from '0,0,0,0,0' to '-30,0,0,30,0'. – Ignore all other parameters, except the signal value which is the first parameter.) After the source of 50, the signal value becomes 50 - 30 = 20. (i.e. The communication vector changed from '-30,0,0,30,0' to '20,1,50,30,1'.) Finally, the Signal value after the load on the right hand side becomes 20 - 10 = 10. (i.e. The communication vector changed from '20,1,50,30,1' to '10,1,50,40,2'.)

At the same instant, the same calculation occurs in the opposite direction from the far right to the left in the upper row starting again with '0,0,0,0,0'. After the load on the far right hand side of figure A.5, the Signal value becomes 0 - 10 = -10. (i.e. The communication vector changed from '0,0,0,0,0' to '-10,0,0,10,0'.) After the source it becomes -10 + 50 = 40 (i.e. The communication vector changed from '-10,0,0,10,0' to '40,1,50,10,1'.) and after the load on the left hand side it becomes 40 - 30 = 10. (i.e. The communication vector changed from '40,1,50,10,1' to '10,1,50,40,2'.) Hence, the signal value in the communication vector changed from '0', to '-10', to '40 and finally to '10', when adding negative values for loads and positive numbers for sources.

As will be seen later, these values will become significant in order for the 'T'-Smart grid to determine whether a particular load can be supplied or not. (Although in the above example all the loads can be supplied, this communication must be repeated initially to finalise the solved states, as will be explained later.)

Note that the simulations only analyses the energy flow (numerical values), and not the actual electrical signals that one would find a Smart grid.

A.3.2 PRIORITY VALUE

Priority values are assigned to sources and loads, based on economic, environmental and control considerations where the lowest priority source will be shed first if the supply exceeds the demand. (See Chapter 4 for more details.)

The load's priority is never communicated between 'T'-components and is not unique per load, as described in Chapter 4.

The source's priority is unique and is communicated between 'T'-components as seen in figure A.5. As can be seen in this figure, the priority value (second parameter) in the communication vector remains zero (unchanged) when it passes through a load connected 'T'-component, but changed to '1' when it passed through the source connected 'T'-component. (This happened for both directions of the communication flow.)

Thus after a source connected 'T'-component, the priority value of the source is communicated to the load connected 'T'-component before and after it. The 'T'-component and its load can now report that it is supplied by a source of priority '1', if there is enough energy to supply the load. If a load was supplied by two sources, then the source priorities would be combined in pro-rata manner as explained in Chapter 4.

For example, assume a grid similar to figure A.5, where the 'T'-component to the far left is a load and the middle and right 'T'-components are sources. Assume the load has an energy requirement of 20 units of energy and the one source has '5' unit of energy available with a priority of '10' and the other source has '15' units of energy available with a priority of '15'. The combined priority calculated in a pro-rata manner would thus be: 5/20 * (10) + 15/20 * (15) = 13.75. Hence, the equation would be (as given in Chapter 4):

$$\text{Supply Priority} = $$

$$\frac{\text{Energy from source connected to grid port 1}}{\text{Total Energy supplied}} \times \text{Supply Priority of Source connected to grid port 1} +$$
$$\frac{\text{Energy from source connected to grid port 2}}{\text{Total Energy supplied}} \times \text{Supply Priority of Source connected to grid port 2}$$

However, in some systems more than two energy sources will have to be combined to supply a load. Assume there are three energy sources and three 'T'-components. In such a scenario, the energy sources from two 'T'-component will be combined together using the above formula, and then that answer will be combined with the third source's priority value of the third source connected 'T'-component, again using the same formula as above. Hence, the pro-rata formula is applied firstly to the two sources, and then re-applied to the answer of this and the third source to arrive at the final pro-rata priority value.

However, in figure A.5, only one source is present and this value is simply relayed to the loads (through the 'T'-components) around it.

Note that for energy storage elements, the priority value will only be relayed to the neighbouring 'T'-components if it is operating in its first mode of operating (emulating a source) or operating in its third mode of operation while discharging energy. When an energy storage element is operating in its second mode of operating (emulating a load) or operating in its third mode of operation while charging energy, its priority value will not be relayed.

A.3.3 ENERGY TOTAL AND LOAD TOTAL VALUES

As the communication vector of (A) passes between 'T'-components, the 'Energy Total' parameter only records the cumulative value of all the energy available (power generation capacity) from all the sources connected to the grid. It adds a zero should a load be connected to a 'T'-component.

Similarly, the 'Load Total' parameter only records a cumulative value of all the loads connected to the grid. It adds a zero should a source be connected to a 'T'-component.

Note that initially, for energy storage elements, only their available energy is recorded (with the 'Total Energy' parameter) and neither their total available energy storage capacity nor their spare energy storage capacity is recorded here.

Together, these two variables ('Energy Total' and 'Load Total') allow the 'T'-components to determine the demand of the grid. (i.e. The 'Load Total' is divided by the 'Energy Total'.)

Grid demand = Total Load / Total Energy (B)

Hence, the grid demand is not communicated as a final value to 'T'-components, but by two separate parameters. (i.e. 'Total Load' and 'Total Energy'.) Later it will be discussed in more detail, why this is necessary.

A.3.4 COUNTER FUNCTION

As discussed in Chapter 4, because different sources can supply the same loads from one simulation increment to another and the fact that the distance over which the energy is transported also changes, a means was devised to accurately capture the SNC for each supply scenario by defining demand zones.

The 'counter' parameter is used to calculate this SNC.

This parameter gets incremented only when the signal value is positive. Hence, as can be seen in figure A.5, the counter (last parameter in the communication vector) is not incremented when it passes through a 'T'-component which has a load connected to it. Once the communication vector passes through the 'T'-component connected to a source, it is incremented. After the source, it is still incremented because there is still energy available. (i.e. the signal value is positive and energy is being transported.)

Once the counter value is determined, then the Shared Network Cost can be calculated.

In this document, only two zones will be considered for explanation and simulation purposes, which will be 'In-zone' and 'Out-zone' as explained in Chapter 4.

Similarly, the load customers must be billed for an intervention, as described in Chapter 4 as well. This will then all form part of the demand value, communicated to customers, that varies between '0' and '4' as given in table 4.1. (Consider Chapter 4 for more details on this.)

Note that only in the case of an intervention, this parameter also used and reported by sources (or energy storage elements in supply mode). This will be explained in more detail, later.

A.4 COMMUNICATION BETWEEN 'T'-COMPONENTS AND GRID-COMPONENTS

Unlike the communication between 'T'-components only, the communication between 'T'-components and Grid-components only require four parameters to be exchanged and its communication vector contains:

[Signal value, Priority, Initial demand (Sources), Grid-component value] (C)

The 'Signal value' and 'Priority' will have the same function as explained earlier for the 'T'-component's communication. (Note however that all parameters from equations (A) to (D) can only take on positive values, except for the signal value of (A), which can become negative due to loads. However, the 'Signal Value' of equation (C) can only take on a positive value due to the 'Grid-component value' used to distinguish between sources and loads, explained later.)

The 'Initial demand' value is only applicable to sources where the owner of the source may have supplied its own load (directly from the source), prior to supplying the grid. (Hence, there is an initial demand on the source, before being connected to the grid.) This allows the owner to record both the external grid demand and actual source demand (and other parameters) which can be used later for maintenance scheduling or expansion and upgrade planning of the source.

The 'Grid-component value' is simply an assigned value to loads and sources for computation and evaluation purposes in the program code. Loads are defined as a '0', and sources a '1'. (Note that if an energy storage element is functioning in the first or second mode of operation, it will simply emulate a source or load Grid-component value, respectively.)

Note that communication between Energy storage elements and 'T'-components differ from the source / load communication vector, when it is operating in the third mode of operation.

Its communication vector is defined as follows:

[Maximum discharge, Maximum charge,
Discharge Charge Priority, Grid-component value] (D)

The 'Maximum discharge' parameter is the maximum energy that can be released, which is available from the energy storage element, taking into consideration the physical limitation (discharge rate) of the energy storage element and the discharging system. Similarly, the 'Maximum charge' parameter is the maximum energy that can be stored, until the energy storage element reaches saturation, while also taking into consideration the physical limitation (charge rate) of the energy storage element and the charging system.

The 'Discharge Charge Priority' parameter is simply a unique priority assigned to the storage element which can either be solved as a load or a source, depending on the grid's requirements, of the 'T'-Smart grid.

Finally, the Grid-component value is defined as a '2' for all Energy Storage Elements functioning in the third mode of operation.

Note that the Energy Storage Elements communicates the vector described in (D) to the 'T'-component, but the 'T'-component responds with a source / load vector as defined in (C).

Hence, if a source vector (C) is sent from an energy storage element (operating in its third mode of operation) to a 'T'-component, then the energy storage element can store the excess energy not used by the grid. If a load vector (C) is sent from an energy storage element (operating in its third mode of operation) to a 'T'-component, and the grid cannot assist with the required energy, then the energy storage element must discharge its available energy that was stored previously to meet the load's request.

A.5. SIMULINK MODELS

The next section gives a high level overview of the models created to simulate the 'T'-Smart grid. This is given to show how the 'T'-Smart grid was developed to achieve the results given in Chapter 5.

Sources, loads and energy storage element models have been programmed in (Matlab) Simulink. The sections to follow shows the Grid-components in simulation block form and gives a brief description of each model's internal workings, processing and evaluation.

Note that the internal clock of all the models are set to 0.0001 second increments and FCLs (mentioned in Chapter 4) can store energy for 0.01 seconds. Hence, there are 100 time increments between 0.0001s and 0.01s for the 'T'-Smart grid to decide and action the optimal grid solution and state change in the 'T'-Smart grid as described in the eight step control process of Chapter 4. Hence, changes in the grid only happen every 0.01 seconds or more.

Note that it is assumed that the FCLs supplied by sources, can continue to give supply for the entire 0.01 seconds. In addition, for computation purposes, the models only have '21' load priorities, '21' energy storage element priorities, and '41' source priorities. This, together with the working of the internal clock will be described in more detail later.

A.5.1 'T'-COMPONENT MODEL

The internal Simulink model layout of figure A.1 is given in figure A.6. Note that there are two grid input / output connection ports for 'T'-components only, and one additional input / output port for Grid-components or 'T'-components connecting to a sub-grid.

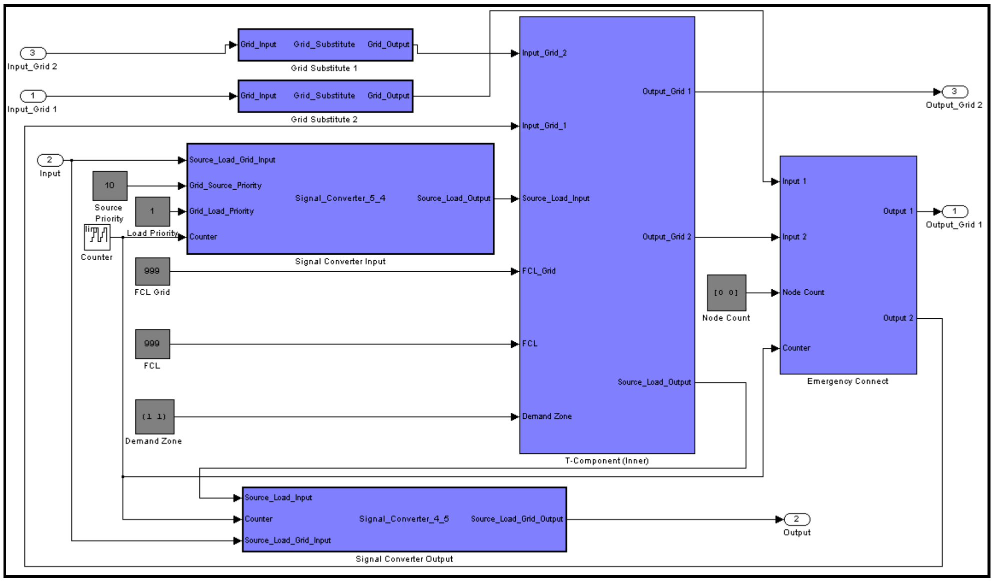

Fig A.6: Internal model layout of the ‘T’-component

Inside the simulation model of the ‘T’-component, one can see ‘Grid Substitute’ (1 and 2) function blocks, ‘Signal Converter’ Input and Output function blocks, the ‘‘T’-component (Inner)’ function block and the ‘Emergency Connect’ function block.

These simulation blocks with their respective tasks will be described next.

A.5.1.1 GRID SUBSTITUTE FUNCTION BLOCK

The function of this block is simply to connect neighbouring ‘T’-components together. If the ‘T’-component is connected on a radial feed and one of the grid connections are left unconnected, then this function block simply substitutes zeros for all the parameters of the communication vector (A), to the remainder of the circuit model. Also, because there are two grid inputs to the ‘T’-component, there are two Grid Substitute blocks used.

A.5.1.2 SIGNAL CONVERTER FUNCTION BLOCKS

The signal converter function block is responsible for managing scenarios where a ‘T’-component is connected to the normal Grid-component connection port (port 3), for supply from or to a sub-grid. As explained earlier, ‘T’-components communicate through a five parameter communication vector given in (A), while Grid-components communicate through a four parameter communication vector given in (C) and (D). This function is responsible for converting communication vector (A) to (C) and vice versa, if a sub-grid is connected to the Grid-component connection port. (Hence, the sub-grid is converted to en equivalent lumped source or load, when interfacing with the main-grid.)

The task of the ‘Signal Converter Input’ block is to first determine whether a source, load, energy storage element or sub-grid is connected to the ‘T’-component. In case of Grid-components, the communication vector used is correct do not require any additional processing. This information is simply sent on to the ‘‘T’-component (Inner)’ block.

However, if a 'T'-component is connected to the Grid-component connection port (for a sub-grid connection), then it must be determined whether the 'Energy Total' is less or more than the 'Load Total' of communication vector (A), sent from the sub-grid. If it is more, then the entire sub-grid can be modelled as a source. If it is less, then the entire sub-grid can be modelled as a load. The 'Energy Total' and 'Load Total' parameters are simply subtracted such that it would give a positive answer and this is then substituted for a 'Signal value' in communication vector (C). A Grid-component value is also added to (C) to indicate whether it is emulating a source or a load before the ''T'-component (Inner)' block processes the scenario further.

This four parameter vector is now fed to the 'T'-component (Inner)' block and the outcome are then fed to the 'Signal Converter Output' block. The block detects whether originally a source, load, energy storage element or sub-grid was connected to it. In the case of a Grid-component, it simply passes the information on as no conversion is required. However, if a sub-grid was connected to it, then it needs to convert the four parameter communication vector given in (C) back to the communication vector given in (A).

Thus, if a sub-grid is connected to the Grid-component connection port, and if the output from the ''T'-component (Inner)' block is a load (hence a load is emulated and communicated to the sub-grid) then the 'Energy Total' is set to zero and the 'Load Total' and 'Signal Value' of communication vector (A) is set equal to the output signal value of communication vector (C), as part of the conversion. The signal value for a load is also made negative to signify a load signal.

Similarly, if the output is a source (hence a source is emulated and communicated to the sub-grid), then the 'Load Total' is set to zero and, the 'Energy Total' and 'Signal Value' of communication vector (A) is set equal to the output signal value of communication vector (C), as part of the conversion. All parameters contain positive values.

Also, as described in Chapter 4, if the input was a load from the main-grid and it requests power from a sub-grid, then its load priority value would be made zero automatically by the 'T'-Smart grid. This is done in order to keep the grid infrastructure to a minimum (for operational and maintenance purposes), and to ensure more sources are created closer to the loads. This rule takes precedence over any other solving rule and thus ensures the sub-grid considers the main-grid's load as the lowest priority it needs to attend to.

Conversely, and also as discussed in Chapter 4, if energy is received from the main-grid, then priority value from the main-grid (which can be a pro-rata value) will be used in the calculations of the sub-grid, as determined by the grid-controllers. There will thus be no change to the priority value and thus the sub-grids loads will be notified that a main-grid source is being used.

Note that if the output vector from the ''T'-component (Inner)' block indicates a source (determined by analysing the Grid-component value in communication vector (C)), then the sub-grid is supplying the main-grid with energy. Conversely, if the output communication vector signified a load, then the main-grid would be supplying the sub-grid with energy. This is because the communication vector data from the ''T'-component (Inner)' always emulates the opposite type Grid-component than required. Hence, a source input signal to the ''T'-component (Inner)' block would respond with a load output communication vector and vice versa.

The final parameter to be assigned in the communication vector (A) is the counter value. If the sub-grid was supplied with energy (the sub-grid is a load), then the counter value would be a one to represent that one main-grid is supplying the sub-grid. Note that the ''T'-component (Inner)' function block would have realised that there was an external grid connected, and increased the demand value accordingly to show that an intervention had occurred as described in Chapter 4.

If the sub-grid was a lumped source, then the counter would remain zero as the sub-grid is supplying the energy and should only profit from supplying the main-grid. Hence, the sub-grid is supplying the main-grid in the same way it would supply a normal load connected to it. The main-grid's demand is then increased accordingly to show that an intervention has occurred because it is acquiring energy from an external source. All of this is recorded and processed by the ''T'-component (Inner)' function block.

A.5.1.3 'T'-COMPONENT MAIN FUNCTION (INNER) BLOCK

The internal model layout of the ''T'-component (Inner)' block of figure A.6 is given in figure A7.

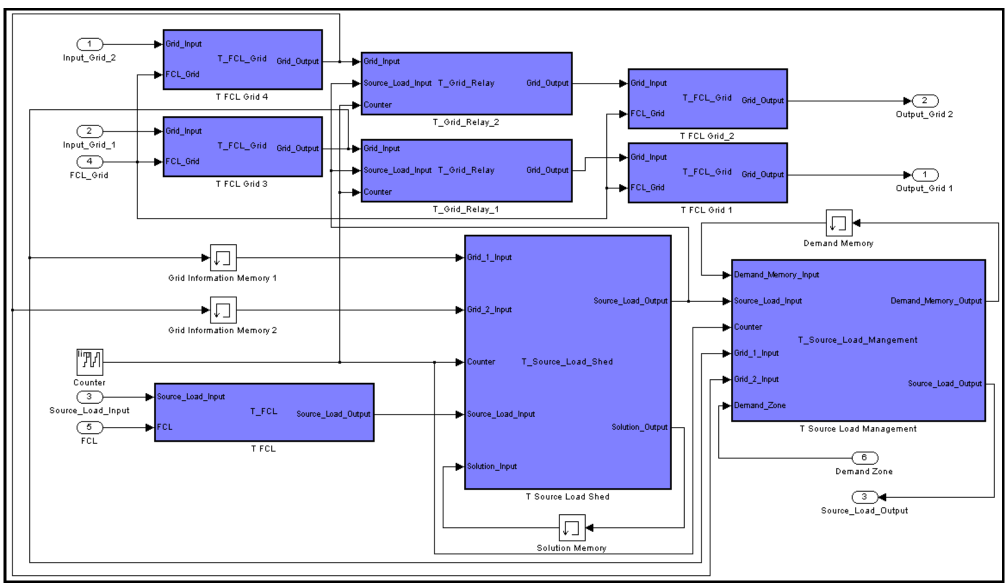

Fig A.7: Internal model layout of the 'T'-component (Inner) block

As can be seen from figure A.7, there is 'T FCL Grid'-, 'T FCL'- , 'T Grid Relay'-, 'T Source Load Shed'-, and a 'T Source Load Management'- sub-function blocks which will be described in the sections to follow.

A.5.1.3.1 T FCL GRID SUB-FUNCTION BLOCK

At the top of the model (figure A.7), there are four blocks labelled 'T FCL Grid', 1 to 4. The purpose of these blocks are simply to limit the amount of energy flowing into the 'T'-component and out of the 'T'-component in accordance with the FCL limit as explained in Chapter 4.

Hence, if the signal value passed through this function exceeds the FCL limit, then this signal must be clamped to the FCL limit. Furthermore, if the difference between the 'Energy Total' and the 'Load Total' of communication vector (A) exceeds the FCL limit, then these parameters must also be clamped to fit inside the FCL limit. This then affects the demand of the grid (or sub-grid), due to limited network / feeder (or FCL) capacity as explained in Chapter 4.

Thus, when the grid FCL's limit is reached, then that point (before or after the connection with the 'T Grid Relay' block) it is reduced to a new single source or load value, depending on the signal. If the 'Signal value' of communication vector (A) is negative and exceeds the FCL limit, then the signal resembles a load and the above recalculation of the demand is thus accomplished by subtracting the 'Total Load' from the 'Energy Total' and then substituting the absolute value of this, as the new 'Load Total' value while the new 'Energy Total' is set to zero. The 'Signal value' takes on the negative value of the new 'Load Total' value.

However, after this the difference between the 'Energy Total' and 'Load Total' is calculated, it may still exceed the FCL limit, and then the 'Load Total' must be set equal to the FCL limit and the 'Signal value' must be the negative of the FCL limit.

Conversely, if the 'Signal value' of communication vector (A) is positive and exceeds the FCL limit, then the signal resembles a source and the above recalculation of the demand is thus accomplished by subtracting the 'Total Load' from the 'Energy Total' and then substituting this, as the new 'Load Energy' value while the new 'Load Total' is set to zero. The 'Signal value' takes on the same value as the new 'Energy Total' value.

However, after this the difference between the 'Energy Total' and 'Load Total' is calculated, it may still exceed the FCL limit, and then the 'Energy Total' must be set equal to the FCL limit and the 'Signal value' to this same value of the FCL limit.

In both case, the 'Priority' value and the 'Counter' value remains unchanged.

In addition, because the possibility exists that there will be 'T'-components connected to the left and right of every other 'T'-component, there are four 'T FCL Grid' function blocks present; one to communicate with the input information being passed from left to right, and one for the input information in the opposite direction. Then, two more blocks are required after the 'T Grid Relay' function block to assess the output of the 'T Grid Relay' function block, again for communication in both directions.

A.5.1.3.2 T FCL SUB-FUNCTION BLOCK

At the bottom left (figure A.7), a similar function is performed by the block titled 'T FCL' which is responsible for applying the FCL limit to incoming signals from Grid-components and sub-grids. This is a much easier operation than what is used for the grid's FCL limit in the five parameter communication vector (A).

In this case, for sources, only the 'Signal Value' of communication vector (C) (four parameter vector) has to be clamped to the FCL limit if it is exceeded. For loads, the signal value must be set to zero if the FCL limit is exceeded because a load cannot be partially supplied. Note that these two options remain the same for sub-grids when they are emulating a source or load as explained in Chapter 4.

In the case of energy storage elements, both the 'Maximum Discharge' and 'Maximum Charge' parameters of communication vector (D) must be clamped to the FCL limit if is exceeded, as explained in Chapter 4.

A.5.1.3.3 T GRID RELAY SUB-FUNCTION BLOCK

The middle top (figure A.7) 'T Grid Relay' function block is responsible for adding sources and subtracting loads from the grid signal as determined by the 'T Source Load Shed' block in middle bottom (figure A.7).

If a source is connected to the Grid-component connection port of the 'T'-component, then this positive value must be added to the 'Signal value' and the 'Energy Total' parameter of communication vector (A). Also, if the signal that was entering the block was already positive, then it resembled a source, which requires that the 'Priority' value be updated in a pro-rata manner based on the amount of energy from the grid input signal and that from the actual source as explained earlier.

Conversely, if a load is connected to the Grid-component connection port of the 'T'-component, then this value must be subtracted from the 'Signal value' and added to the 'Load Total' parameter of communication vector (A), if allowed by the 'T Source Load Shed' block. If after subtracting the load's value from the 'Signal Value', the remaining 'Signal value' is positive, then the priority value will remain unchanged.

However, if after subtracting the load value from 'Signal value' results in a negative 'Signal value', and if allowed by the 'T Source Load Shed' block, then the priority value would be-assigned a zero value as there are no remaining energy and hence no priority value to be communicated. (As mentioned previously, only source priority values are communicated between 'T'-components in the five parameter communication vector of equation (A), if the energy is available.)

The Counter value is also incremented by this function block, to assist in the calculation of demand zones later. The counter is only incremented if the output signal is positive (hence a source). This is done to determine the furthest source left and right of a given load (to supply it), and so to charge extra for the SNCs incurred to supply the connected load.

Note however that at every second time increment in a given grid state, all the nodes ('T'-components) irrespective of what is connected to it, is counted and forms part of the protection explained later under the internal function of the 'Emergency Connect' block. This true counter value of all 'T'-components is then relayed only at this time increment, instead of the actual counter value used for determining demand zones, by this sub-function block.

In addition, because the possibility exists that there will be 'T'-components connected to the left and right of every other 'T'-component, there are two 'T Grid Relay' function blocks present (figure A.7.); one to communicate with the information being passed from left to right, and one for information being passed the opposite direction.

A.5.1.3.4 T SOURCE LOAD SHED SUB-FUNCTION BLOCK

The 'T Source Load Shed' function block is the most important function block inside the 'T'-component as it determines the grid solution. Its purpose is to shed or reduce energy from sources and to shed energy supply to loads, if required. It is also responsible for the management energy storage elements.

Note the 'counter' shown in figure A.7. This 'counter' has no relation to the counter value used for demand zone calculations, and is a Simulink function that counts from 0 to 99. The counter's value is incremented every 0.00001 seconds until it reaches 99, after which it resets to zero. (The Simulink models' time step is also set at 0.00001 seconds.) Hence, there are 100 time step for the grid to solve itself until a new grid state is reached, as mentioned earlier.

Because, there are only 100 time steps, the grid changes state every 0.00001 * 100 = 0.01 seconds. Hence, the FCL's from sources and energy storage elements (functioning in a discharging state) are storing the energy for 0.01 seconds before supplying the grid at the next grid state for 0.01 seconds. Loads and energy storage elements (functioning in a charging state) only request this energy during this time, and only receives it (if is there sufficient energy available and adequate grid infrastructure) at the next grid state.

This 'counter' is found throughout all the models and all perform the same function. That is, at every time step from 0 - 99 certain program thread(s) is executed so that by the end of the 99 increments, the grid has reached a new solved state.

Inside the 'T Source Load Shed' function block, the grid is solved by continuously monitoring the sum of the 'Energy Total' and the 'Load Total' from the communication vectors (A) sent in both directions through the 'T'-component. In addition, if a source is connected to the 'T'-component its signal value is added to the 'Energy Total' value, or if a load is connected to the 'T'-component its signal value is added to the 'Load Total' value. (This then defines the 'Total Source' and 'Total Load' values as described in Chapter 4.) Then, as per the system control process explained in Chapter 4, load is shed until the available energy matches or exceeds the grid's load requirements.

Note that if energy storage elements are operating in their third mode of operation, it is initially modelled as sources, until all the loads have been considered. Then, if energy from the storage elements is required to supply the loads, then it is used. If there is more than sufficient energy available from the sources alone, then the energy storage elements are modelled as loads to store the excess energy. If energy remains after all the energy storage elements have been supplied, then less energy is requested from the sources and this excess energy is lost. (Consider Chapter 4 for more details.)

The above is achieved by shedding loads in the time steps 5 to 25, with each time step representing a different priority of loads. (i.e. time step '5' means that all the priority zero loads are shed up to time step '25' which means that the last priority '20' loads are shed.) Hence, all loads with the same priority are shed in the entire grid at the same time. (Consider Chapter 4 for more details.)

In the time steps 30 to 50, all energy storage elements (functioning in the Third mode of operation) are considered; first as a source and then as a load. (Time step 30 corresponds with a priority 0 energy storage element and time step 50 corresponds with a priority 20 energy storage element.) That is, if energy from a particular energy storage element is needed (and it has energy available) to supply the grid, then it is used as a source. However, if it is not needed (and it has energy storage capacity available), then it is used as a load to store energy. (Consider Chapter 4 for more details.)

The above is achieved by converting communication vector (D) to communication vector (C), with the 'Initial Demand' set to zero and using the energy storage element's 'Discharge Charge Priority' as the functional priority value; and then a source or load is emulated as needed. The 'Maximum Discharge' is used for the 'Signal value' for a source, and the 'Maximum Charge' as the 'Signal value' for a load. After the grid is solved by the 'T Source Load Shed' function block, and although the energy storage element communicated a vector in the form of (D) to the 'T'-component, the 'T'-component would respond with a communication vector in the form of (C) where a source vector would mean that the energy storage element needs to store energy and a load vector would mean the storage element needs to be discharge energy into the grid.

Finally, in the time steps 55 to 95, all sources are considered. (Time step 55 corresponds with a priority 0 source and time step 95 corresponds with a priority 40 source.) At this time all necessary loads have been shed, and energy storage elements are either charging or discharging energy. Thus, the only task left is to shed or reduce (if necessary) the sources such that the grid's load requests (together with those of the energy storage elements, if applicable) matches the available energy of the sources exactly (after available energy have been taken into account). (Consider Chapter 4 for more details.)

Consider the control method and flow diagram explained in Chapter 4, which is similar to what is explained above. The solution (control method) is executed in 100 time steps, to end in a solved grid state every 0.01 seconds. This is then repeated every 0.01 seconds as the grid states changes. This solution, once it is reached, is recorded and stored in the 'Solution Memory' block as seen in figure A.7. (Some extra details of this will be given later.)

As previously discussed in Chapter 4, external grids are assigned priority values and are solved as normal lumped loads or sources and are thus dependent on their priority values.

A.5.1.3.5 T SOURCE LOAD MANAGEMENT SUB-FUNCTION BLOCK

The function of the 'T Source Load Management' function block is to assign the calculated priority and demand values to the Grid-components connected to the Grid-connection port of the 'T'-component.

If a load is connected to the 'T'-component (or an energy storage element in charging mode, as determined by the 'T Source Load Shed' function block), and it is not shed, then it must be determined whether energy from only one side (left or right of the 'T'-component) is needed to supply the load, or form both sides. If energy is required from both sides, then the source priority must undergo a pro-rata calculation as described earlier (and in Chapter 4), and communicated to the load.

The grid demand must also be calculated and communicated to the load. This is done by measuring and recording the demand at time step 3 (before loads are shed) and time step 27 (after all necessary loads have been shed, before considering energy storage elements). Thus, if there were initially at time step 3 not sufficient energy to supply the load, then an 'intervention' had to occur to supply the load. (i.e. load shedding occurred or and external-grid source was used.)

Note that at time step 3 and 27, an empty matrix (i.e. [0 0 0 0]) is substituted in the calculation for all external grids so that it would not be taken into account by this demand calculation, irrespective of its assigned priority of the external grid. Consider Chapter 4 for more details. (This function is performed by the 'Signal Converter' function shown in figure A.6.)

After time step 3, if the grid's total load exceeded the total energy, it can assumed that an intervention occurred, however, the demand measurement taken at time step 27 (without the external grid's influence) will give the new actual demand of the grid. Independent of whether loads had been shed before time step 27 or not, the demand is then calculated by using equation (B). The only difference is that if a load needed to be shed to supply the grid, then an intervention alarm would have been triggered. Hence, if load was shed, and the total load is now less than the total energy, then equation (B) would be valid together with a constant value '2' added to demand (to signify an intervention) as described in Chapter 4.

Else, if no intervention occurred, then this addition would not be needed. However, if the total load still exceeded the total energy value, at time step 27, then external sources (from an external grid) supplied the load (because it was not taken into account when this demand calculation was made) and the demand is defined as '1' (100%), plus '2' because of an intervention that was recorded at time step 3. The demand value of the grid becomes '1' because only the absolute minimum energy needed to supply the grid is obtained from the external grid, as explained in Chapter 4. Thus, the total load will match the total energy consumption exactly. (This information is stored inside the 'Demand Memory' block, and is updated by the 'Demand Memory Output' function which feeds the updated value back into the 'Demand Memory Input' port as seen in figure A.7.)

At time step 98, the counter value of communication vector (A), which counts the source nodes ('T'-components with sources connected to it) left and right of the 'T'-component is compared to the pre-defined in-zone parameter and its applicable number of nodes. In figure A.6, the demand zone was defined as [1 1]. (This is an input to the ''T'-component (Inner)' function block which is passed on directly to the 'T Source Load Management' function block.) This input indicates that if a source is connected to the first 'T'-component left or right of the 'T'-component being considered (to which the load is connected), then those sources would be considered in-zone and all other source that are further away would be out-zone. Hence, it is determined whether the sources that are supplying the load are in-zone or out-of-zone and then the demand value is modified by adding a '1', if it is out-of-zone. (Consider Chapter 4 for more details.)

This concludes the final priority and demand value assignment to a load.

For sources, independent on whether it is supplying loads to the left of it, or to the right, or both sides, it just communicates its priority value to those loads. The same demand value as calculated for loads (and the grid) are communicated to the source, together with whether an intervention has occurred or not. Demand zones are not communicated to sources, as it is supplying the energy and the loads are responsible for the network costs associated with transferring the energy. (This is an assumption of the 'T'-Smart grid.)

This concludes the final priority and demand value assignment to a source.

Finally, whether a source signal or a load signal is communicated out by the 'T Source Load Shed' function block , if the load was shed or the entire source was not used, then the 'Signal values' will be assigned a zero value and the 'Priority' and 'Initial Demand' values will be assigned a minus 1 ('-1', as opposed to a zero) value, so that it would not be confused with sources or loads with a zero priority or be confusing in a situation where the grid's demand is zero.

Note that as discussed earlier, the 'T'-component communicates source or load singles back to the energy storage elements, depending on their mode of operation, as discussed earlier. Hence, the above remains applicable, depending on whether the energy storage element is receiving a source or load signal. The same is true for sub-grids.

A.5.1.4 EMERGENCY CONNECT FUNCTION BLOCK

The internal model layout of the 'Emergency Connect' function block of figure A.6 is given in figure A.8.

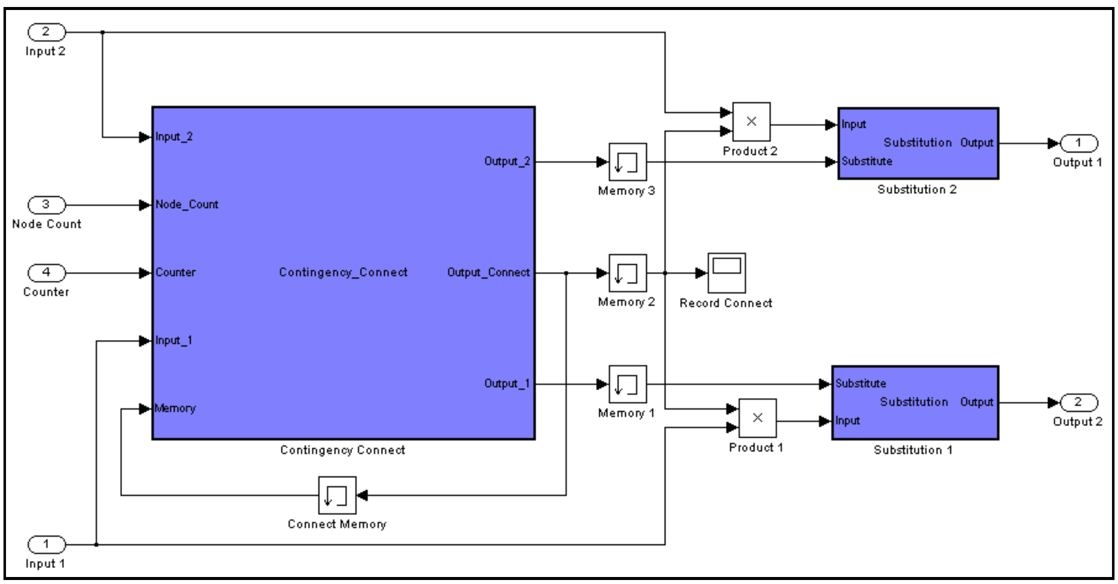

Fig A.8: Internal model layout of the 'Emergency Connect' function block

The 'T'-Smart grid, like current grids and future grids have a wide range of protection methods to safeguard the network. In addition to the limiting the fault current with an FCL in a 'T'-Smart grid and measuring the discharge rate from the FCL as means to sense a fault (as mentioned in Chapter 4), a condition must be defined when a (N/O) connections may be closed to obtain supply from another source if a fault occurred on the grid.

As explained in Chapter 4, another protection method of the 'T'-Smart grid is to count the number of 'T'-components left and right of it (irrespective of the Grid-component connected to it), and then to count and verify if this number of the 'T'-components is still available at each grid state increment. Thus initially, all 'T'-components left and right of a given 'T'-component is known and programmed into the 'T'-component. (Consider figure A.6 and the 'Node Count' variable which is an input to the 'Emergency Connect' function block.)

Then, at the second time increment (as mentioned previously), a given 'T'-component counts the 'T'-components left and right of it and compares it to the pre-programmed value ('Node Count'). If the numbers do not match, then the N/O is changed to an N/C in the network, or it is used to connect to another network. This is only applicable for 'T'-components that have an N/O connection point left of it. (i.e. Input 1 and Output 1 are the only ports that support this function.)

As can be seen in figure A.6, the node count is assigned a '[0 0]' value, which is the pre-programmed number of 'T'-components that should be detected under normal operation. The first value is for the number of 'T'-components left and the second parameter for the number of 'T'-components to the right of the 'T'-component under consideration. However, a '[0 0]' value is unique and this setting is used when a 'T'-components must have permanent connections to the left and right of it, and hence has no N/O connection point.

The 'Substitution' function blocks (figure A.8) prevents energy from flowing under normal conditions, if there is an N/O operation point and the fault has not yet occurred. It only substitutes '[0 0 0 0 0]' in the form of communication vector (A), to the neighbouring 'T'-components, to make it an open connection port.

As explained previously and in Chapter 4, the N/O will change to an N/C connection once a fault it detected. If the fault is then later cleared, the N/C connection will be changed back to an N/O connection. This is the function of this block.

Note that the author attempted to simulate ring type networks, but the software (Matlab) version used did not support this function. Hence, only radial networks are simulated and N/O connections to close the network ring, or to connect to another network, are only switched to Normally Closed (N/C) when faults occur.

A.5.2 SOURCE MODEL

The internal model layout of a source (figure A.2) is given in figure A.9.

In figure A.2 and figure A.9, there are four inputs, numbered one to four with one output to the external model. For the moment, 'Input 1' will be ignored.

Input 2 takes samples of the positive signal value of the available energy resource and multiplies it with a matrix to store this value in the appropriate place in the communication vector (C) described earlier. The Priority value undergoes the same process but is limited to positive integer values, from 0 to 40 (hence, 41 available values). This is achieved through taking the absolute value of the input, using the saturation function to limit the priority numbers and rounding off to ensure it is an integer value.

The initial demand signal of input 3 is also placed in the correct position inside the communication vector, and the input is made positive and restricted between 0 and 0.99. This is because the demand value will always be positive and the initial demand cannot be '1', as then the input signal value will have to be 0. (As mentioned earlier, the initial demand represents the energy already used by the owner of the source, prior to selling the remainder not being used.) Finally, a '1' is added (as Grid-component value) to the end of the communication vector to signify that this is an available energy source.

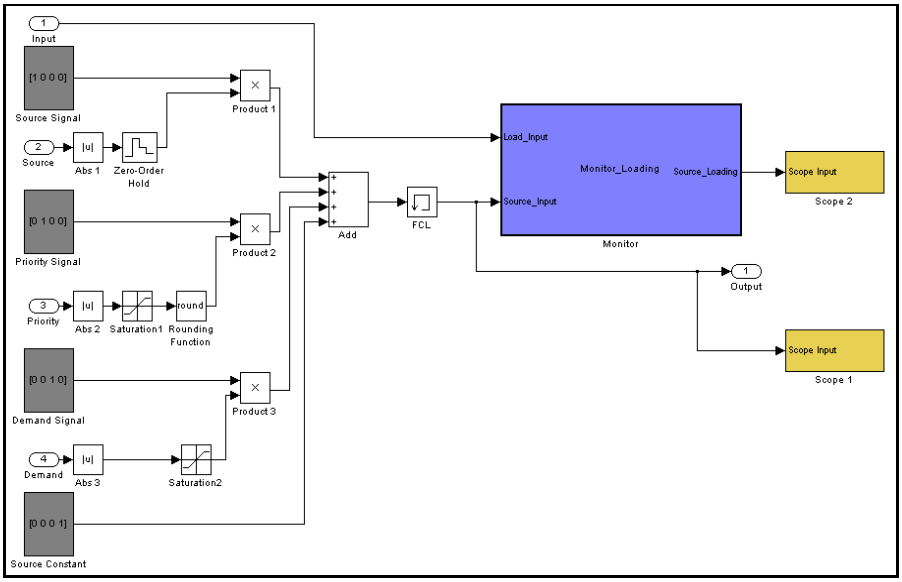

Fig A.9: Internal model layout of Sources

All of the previous mentioned parameters inside the communication vector are fed to the FCL which delays its output by 0.01 seconds. (This assists with the solving of the grid as mentioned in Chapter 4.) After 0.01 seconds elapsed, the grid will have realised a decision and then this energy is sent into the grid through 'Output 1', if the grid requires the energy. At the same instant, because the 'T'-Smart grid was aware of the available energy, it responds with the amount of energy that is to be used through 'Input 1', if any. Note that the communication being received is in the form of a load vector ending in a '0'. This is to signify that the available energy is now being used and the quantity thereof is being reduced, inside the FCL.

In addition to the amount of energy that is being used and communicated through 'Input 1', it also communicates back the source's priority previously sent out from 'Output 1' (to confirm and audit the correct operation), together with the grid's demand. From this, the blue 'Monitor' block (figure A.9) records the amount of energy used, the priority of the source as assigned by the grid operator, the actual demand of the source and the grid's demand as explained in Chapter 4.

From figure A.9, there are two 'Scope' blocks indicates. The internal layout of Scope 1 is given in figure A.10.

The scope only aids in recording input and output communication between Grid-components and the 'T'-component. Although this data can be viewed in Simulink, it is exported to Matlab and formatted into graphs for explanation purposes in Chapter 5. Note that this type of scope (Scope 1) is common to loads and energy storage elements. However, only Scope 2 is unique to sources as it records both the actual demand and grid demand, separately. This is shown in figure A.11.

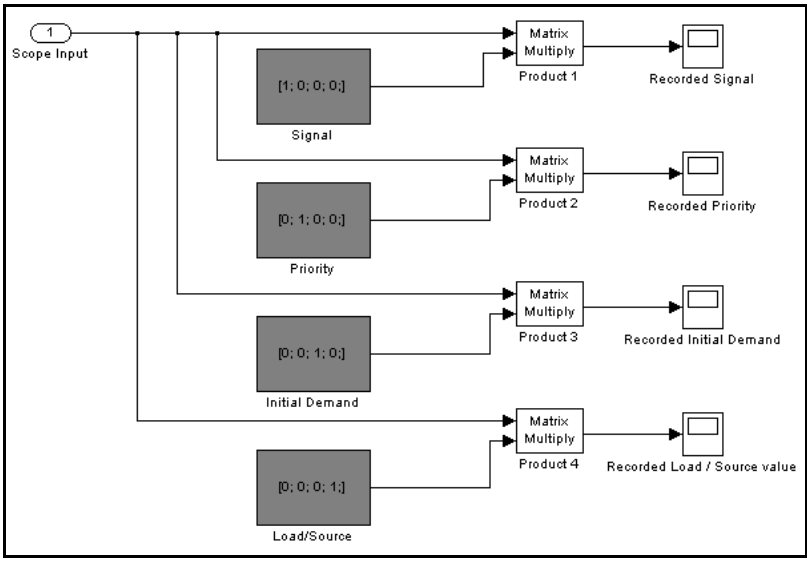

Fig A.10: Internal model layout of a Scope 1 (inside Sources)

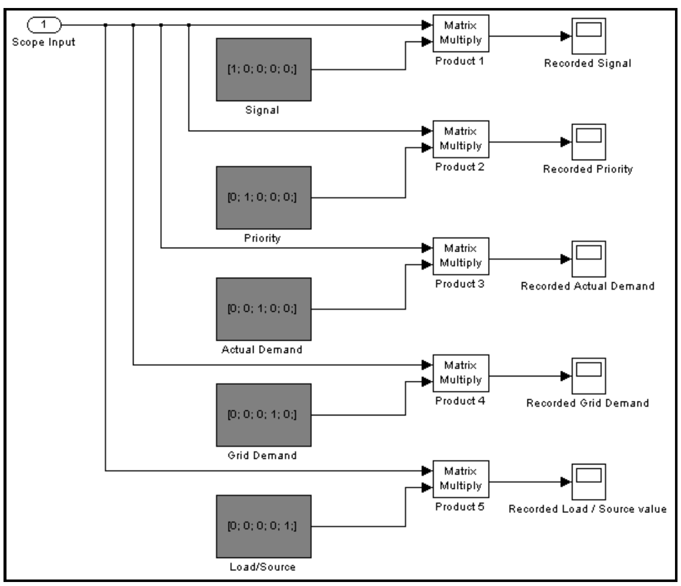

Fig A.11: Internal model layout of Scope 2 (inside Sources)

A.5.3 LOAD MODEL

The internal model layout of a load (figure A.3.) is given in figure A.12.

Similar to the source, the load's energy request is described as a positive signal value which is combined with its priority into a communication vector (C). Note that the load's priority values are positive integer values limited between 0 and 20 (hence, 21 values). Also note that it is not necessary to add a '0' at the end of the communication vector (for the Grid-component value), as there is already a '0' added from the previous vector multiplication.

This request for energy is now stored inside the FCL, while in actual fact it is empty. This request is stored for 0.01 seconds and while being stored, the grid is already made aware of it. Once this period passes, 'Input 1' receives a source signal (together with the 'Grid-component value' set to 1) to indicate whether the load can be supplied or whether it has to be shed. (A zero signal value indicates that the load is shed.) It also receives information about the priority of the source it is being supplied with (or pro-rata value if there are many sources), and the grid's demand if it were to be supplied. (This information is again processed by the blue block labelled 'Monitor' in figure A.12.)

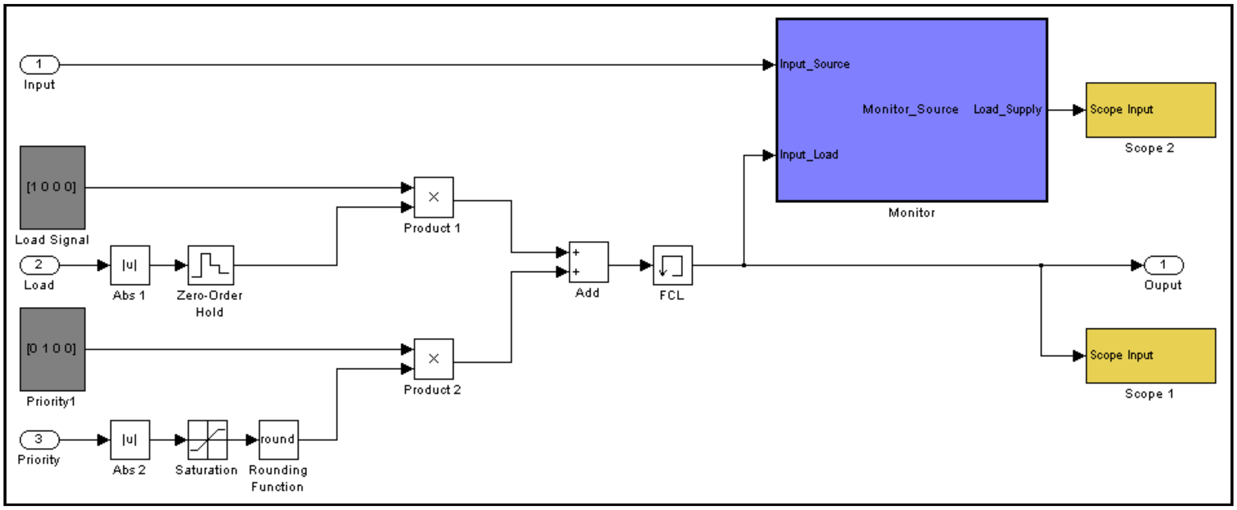

Fig A12: Internal model layout of Loads

Scope 1 and Scope 2 shown in figure A.12 that records the energy and grid information, is exactly the same as Scope 1 shown in figure A.10. The only difference that it records the demand of the grid, instead of the initial demand, as can be seen in figure A.13.

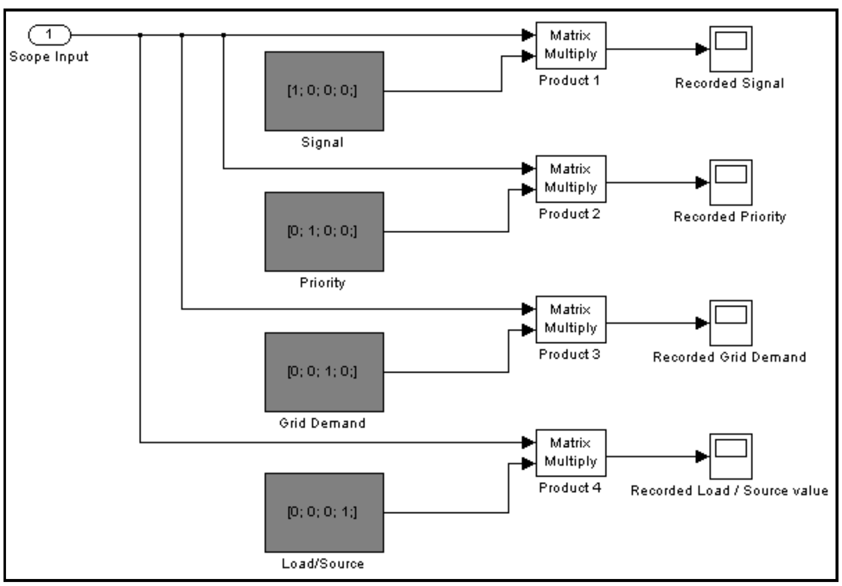

Fig A.13: Internal model layout of Scope 1 and Scope 2 (inside Loads)

A.5.4 Energy Storage Element Model

The internal model layout of an energy storage element (figure A.4.) is given in figure A.14.

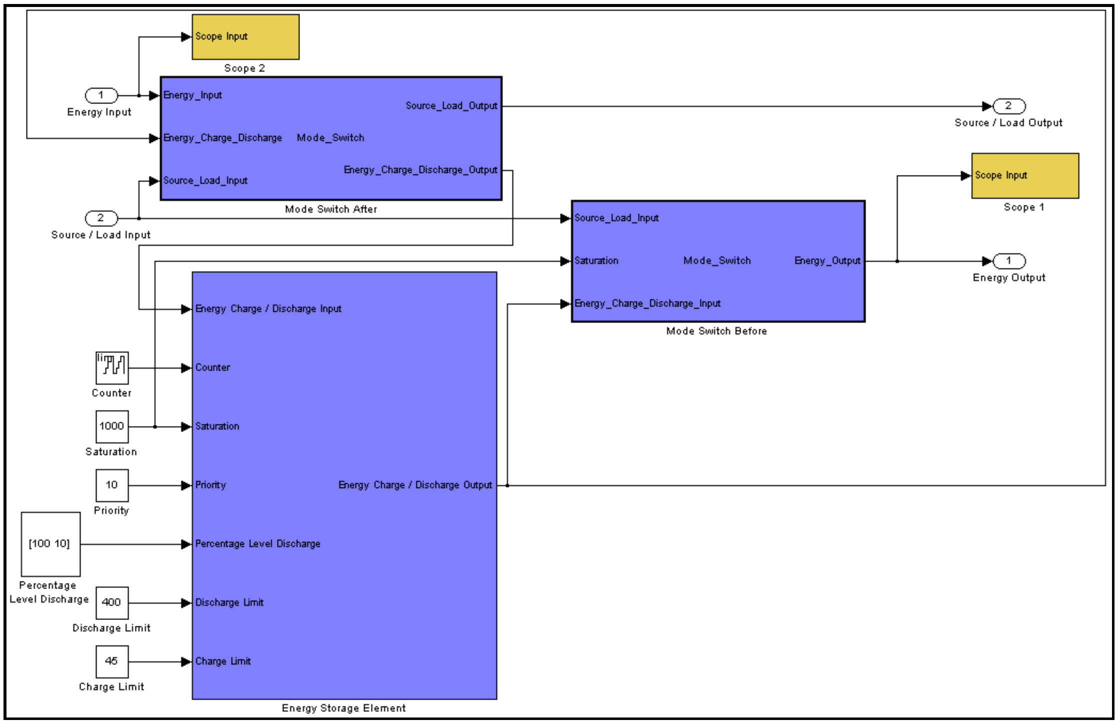

Fig A.14: Internal model layout of Energy Storage Elements

As seen in figure A.14, the internal model for the energy storage element comprises of two function blocks referred to as the: 'Mode Switch' functions ('before' and 'after') and the Main function described in the sections to follow.

A.5.4.1 Mode Switch function Blocks (Before and After)

The Energy Storage Element has two inputs and two outputs. This is because the Energy Storage Element can connect between Grid-components and the 'T'-component, in the first and second mode of operation. Hence, one input and output is connected to the grid and the other input and output is connected to the Grid-component. In the third mode of operation, the second input and output set is simply left unconnected. (Consider Chapter 4 for more details regarding the different modes in which the energy storage element can operate.)

In figure A.14, the 'Mode switch before' and 'Mode switch after' determines in what operation the Energy Storage element is being used and ensures that the actual storage medium is managed as described in Chapter 4 for sources and loads (First and Second mode of operation).

Note that in this model, the constant energy charging rate requested is 1 % of the saturation capacity of the energy storage medium or the charging limit of the storage medium, whichever is less, for the second mode of operation. This rate will most likely be intelligently modified in future, as explained in Chapter 4.

If it were to operate on its own (Third mode of operation), then it would simply relay the grid's information to the 'Energy Storage block' and rely its response back to the grid. The reason for this is that Energy Storage Elements in general, was mainly designed for this mode of operation (third mode). The sections to follow will discuss this more in detail.

Hence, these two blocks ('Mode switch before' and 'Mode switch after') determines the mode of operation of the Energy Storage Element and then emulates the correct communication vector based on its mode of operation and communicates this to the 'Energy Storage Element' block. (This will be explained in more detail in the sections to follow.)

A.5.4.2 MAIN FUNCTION BLOCK

The Energy Storage Element block is essentially the actual representation of the device and that which was discussed previously is only part of the management and communication with the 'T'-component in the 'T'-Smart grid. Consider figure A.15, which is an enlarged view of the Energy Storage Element block.

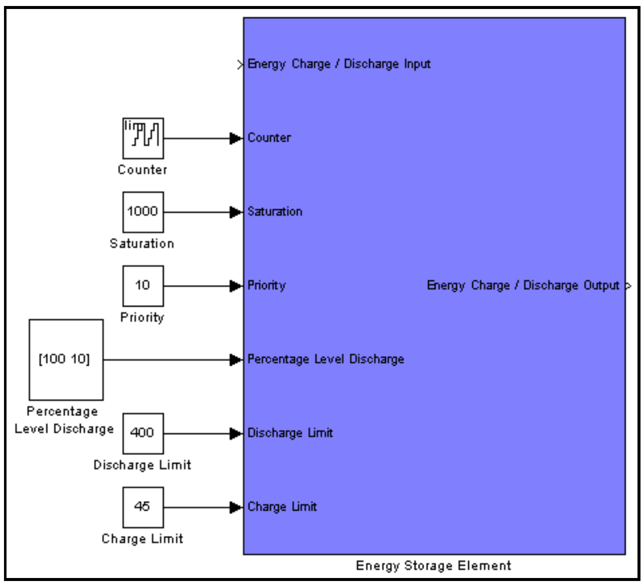

Fig A.15: Energy Storage Element function block

As can be seen in figure A.15, in addition to the input and output to the Energy Storage function block, there are six additional inputs all related to physical characterises of energy storage elements and other secondary controls to modify its behaviour.

The counter, which was discussed with the 'T'-component, is responsible for counting 100 time intervals between the grid's state changes, which changes every 0.01 seconds. During this time, the Energy Storage Element communicates with the 'T'-component grid and makes its own decisions for optimal charging and discharging of energy. (This is explained in more detail after figure A.16.)

The saturation parameter restricts the energy storage element from charging more energy than is physically possible, as discussed in Chapter 4.

The priority value is unique (as discussed in Chapter 4) and is limited to values from 0 to 20 (hence, 21 values) for simulation purposes. For the First and Second mode of operation, the priority value seen in figure A.14 and figure A.15 is ignored and the priority of the source or load is assumed as discussed in Chapter 4.

This priority value, as previously mentioned, is only applicable and used when the energy storage element is functioning in its Third mode of operation. (Consider Chapter 4 for more details.)

Consider figure A.16, as part of the explanation of the 'Percentage Level discharge', 'Discharge Limit' and 'Charge Limit' parameters explained in the sections to follow. This figure is the sub-internal model layout of the Energy Storage Element function block given in figure A.15.

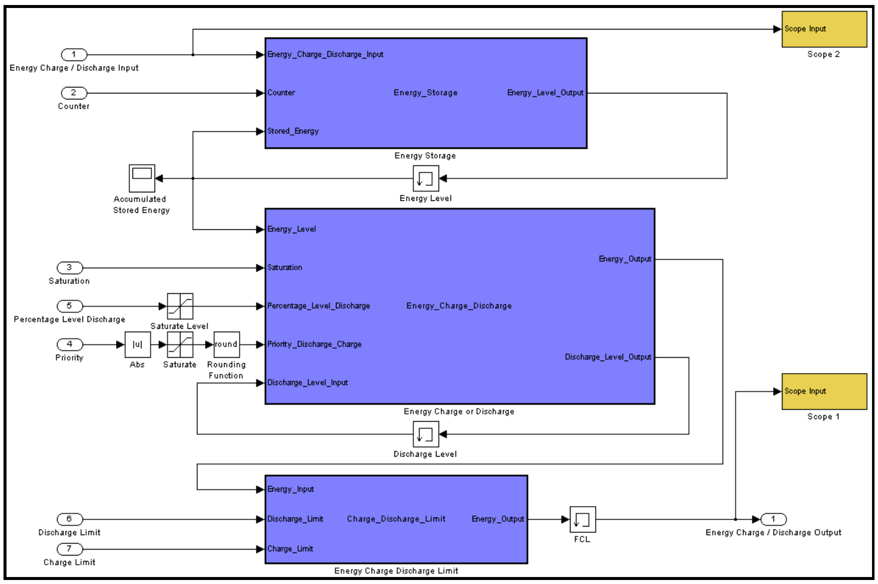

Fig A.16: Internal model layout of the Energy Storage Element function block

A.5.4.2.1 ENERGY STORAGE SUB-FUNCTION BLOCK

As can be seen from figure A.16, the 'Energy Storage' block (upper blue block) is a sensing circuit which is tasked to keep record of the amount of energy stored or released for a given solved state of the grid.

A.5.4.2.2 ENERGY CHARGE OR DISCHARGE SUB-FUNCTION BLOCK

The 'Energy Charge or Discharge' block (middle blue block) in figure A.16 takes input such as the 'Saturation', 'Percentage Level Discharge' and the 'Priority' and performs an important function to ensure grid stability which can override the grid's request to charge or discharge energy, as explained in Chapter 4.

Consider figure A.16, where the input of the 'Percentage Level Discharge' is set to '[100 10]'. The first parameter is the percentage saturation level at which it must stop charging, before allowing the energy storage element to discharge. The second term is the percentage saturation level where it must stop discharging until it has been recharged to its previous defined charged level (100%), as explained in Chapter 4.

Once the previous mentioned parameter has been set, the 'Energy Charge or Discharge' block (middle blue block) compiles the information in the form of communication vector (D) which consists of the maximum energy that is available for discharge, the maximum energy that can be charged before saturation, the assigned priority of the Grid-component and its unique Grid-component value of '2' to signify it is an energy storage element as described earlier.

Note that the maximum discharge parameter will always be zero in the second state of the energy storage element, mentioned previously. Hence, if the actual energy level falls below the energy level specified by the second parameter of the 'Percentage Level Discharge' value, then the maximum discharge rate communicated will be a zero (in communication vector (D)), until the energy level of the first parameter (of the 'Percentage Level Discharge' value) is reached.

As can be seen in figure A.16, the 'Percentage Level Discharge' input has a saturation function to ensure that the values entered for both the first and second parameters is limited to between 0 and 100% as these levels will always be a fraction of the energy storage element's saturation level.

The priority is again limited through a series of functions, as done previously, to be a positive integer value ranging from 0 to 20. (Hence, there are 21 available priority values.)

All this information, together with the output maximum discharge and charge parameters (with the Grid-component value of '2') is communicated to the last 'Energy Charge Discharge limit' (bottom blue) block in figure A.16.

A.5.4.2.3 ENERGY CHARGE / DISCHARGE LIMIT SUB-FUNCTION BLOCK

The final 'Energy Charge Discharge Limit' block (bottom blue block) in figure A.16 is responsible for the modeling of the physical limitations of the charging and discharging rate based on the type of energy storage medium used as explained in Chapter 4.

Both parameters are chosen to be constant in this model for simulation reasons. Note that these limits can be higher or lower than the limit of the FCL. However, between these limits and the limit of the FCL, the lower value will determine the final charge and discharge rate.

This information is then fed through the FCL to the 'Mode Switch Before' function block explained earlier. The 'Mode Switch Before' will send a communication vector (D) to the 'T'-component if the energy storage element is operating in its third mode of operation, or alternatively it will send a communication vector (C), if it is operating in any of the first two modes of operation.

It will however always receive a signal from the 'Mode Switch After' function block in the form of communication vector (C), depending on whether the 'T'-component decided to use it as a source (discharge it) or to store energy in it (charge it).

A.6 'T'-SMART GRID MANAGEMENT TASKS

As mentioned earlier in this chapter, an internal clock (represented by a 'Counter' in Simulink) counts 100 time steps between grid states, in which the 'T'-Smart grid must solve all the grid parameters and network connections. Sources and loads do not require this and only communicate and process a small amount of information in an analogue fashion. '

T'-components and Energy storage elements (functioning in the Third mode of operation) on the other hand, have to communicate and process a large amount of information and does so in a digital fashion. Hence, at each digital step increments of 100 steps between grid states, specific tasks are being performed as detailed in Chapter 4.

A summary of these tasks, performed by 'T'-components and Energy storage elements are given in table A.1, together with the time steps at which this function is being performed. This resembles the flow chart for the control of the 'T'-component, as explained in Chapter 4.

Table A.1: Internal clock increments between grid states and associated tasks

Counter	**Task executed by the 'T'-component on a given time step.**
0	Execute all negotiated connections determined during previous grid state.
1	Disconnect all connections to reset the system.
2	Count all nodes (to detect a fault), and reconnect all normal installation connections that do not have a fault, and close the applicable N/O connections if a fault occurred (if available).
3	Disconnect external grid for demand measurement and capture initial demand.
4	-
5	Consider whether loads of priority 0 must be shed or supplied.
6	Consider whether loads of priority 1 must be shed or supplied.
7	Consider whether loads of priority 2 must be shed or supplied.
8	Consider whether loads of priority 3 must be shed or supplied.
9	Consider whether loads of priority 4 must be shed or supplied.
10	Consider whether loads of priority 5 must be shed or supplied.
11	Consider whether loads of priority 6 must be shed or supplied.
12	Consider whether loads of priority 7 must be shed or supplied.
13	Consider whether loads of priority 8 must be shed or supplied.
14	Consider whether loads of priority 9 must be shed or supplied.
15	Consider whether loads of priority 10 must be shed or supplied.
16	Consider whether loads of priority 11 must be shed or supplied.
17	Consider whether loads of priority 12 must be shed or supplied.
18	Consider whether loads of priority 13 must be shed or supplied.
19	Consider whether loads of priority 14 must be shed or supplied.
20	Consider whether loads of priority 15 must be shed or supplied.
21	Consider whether loads of priority 16 must be shed or supplied.
22	Consider whether loads of priority 17 must be shed or supplied.
23	Consider whether loads of priority 18 must be shed or supplied.
24	Consider whether loads of priority 19 must be shed or supplied.
25	Consider whether loads of priority 20 must be shed or supplied.
26	-
27	Disconnect external grid for demand measurement and capture new actual demand. Determine and communicate to loads if an intervention occurred.
28	-
29	-

Table A.1: Internal clock increments between grid states and associated tasks (Continued)

Counter	Task executed by the 'T'-component on a given time step.
30	Consider whether an Energy Storage Element of priority 0 must discharge its energy, store excess energy or just be disconnected.
31	Consider whether an Energy Storage Element of priority 1 must discharge its energy, store excess energy or just be disconnected.
32	Consider whether an Energy Storage Element of priority 2 must discharge its energy, store excess energy or just be disconnected.
33	Consider whether an Energy Storage Element of priority 3 must discharge its energy, store excess energy or just be disconnected.
34	Consider whether an Energy Storage Element of priority 4 must discharge its energy, store excess energy or just be disconnected.
35	Consider whether an Energy Storage Element of priority 5 must discharge its energy, store excess energy or just be disconnected.
36	Consider whether an Energy Storage Element of priority 6 must discharge its energy, store excess energy or just be disconnected.
37	Consider whether an Energy Storage Element of priority 7 must discharge its energy, store excess energy or just be disconnected.
38	Consider whether an Energy Storage Element of priority 8 must discharge its energy, store excess energy or just be disconnected.
39	Consider whether an Energy Storage Element of priority 9 must discharge its energy, store excess energy or just be disconnected.
40	Consider whether an Energy Storage Element of priority 10 must discharge its energy, store excess energy or just be disconnected.
41	Consider whether an Energy Storage Element of priority 11 must discharge its energy, store excess energy or just be disconnected.
42	Consider whether an Energy Storage Element of priority 12 must discharge its energy, store excess energy or just be disconnected.
43	Consider whether an Energy Storage Element of priority 13 must discharge its energy, store excess energy or just be disconnected.
44	Consider whether an Energy Storage Element of priority 14 must discharge its energy, store excess energy or just be disconnected.
45	Consider whether an Energy Storage Element of priority 15 must discharge its energy, store excess energy or just be disconnected.
46	Consider whether an Energy Storage Element of priority 16 must discharge its energy, store excess energy or just be disconnected.
47	Consider whether an Energy Storage Element of priority 17 must discharge its energy, store excess energy or just be disconnected.
48	Consider whether an Energy Storage Element of priority 18 must discharge its energy, store excess energy or just be disconnected.
49	Consider whether an Energy Storage Element of priority 19 must discharge its energy, store excess energy or just be disconnected.
50	Consider whether an Energy Storage Element of priority 20 must discharge its energy, store excess energy or just be disconnected.
51	-
52	-

Table A.1: Internal clock increments between grid states and associated tasks (Continued)

Counter	Task executed by the 'T'-component on a given time step.
53	-
54	-
55	Consider whether a source of priority 0 must be used (in total), reduced or disconnected.
56	Consider whether a source of priority 1 must be used (in total), reduced or disconnected.
57	Consider whether a source of priority 2 must be used (in total), reduced or disconnected.
58	Consider whether a source of priority 3 must be used (in total), reduced or disconnected.
59	Consider whether a source of priority 4 must be used (in total), reduced or disconnected.
60	Consider whether a source of priority 5 must be used (in total), reduced or disconnected.
61	Consider whether a source of priority 6 must be used (in total), reduced or disconnected.
62	Consider whether a source of priority 7 must be used (in total), reduced or disconnected.
63	Consider whether a source of priority 8 must be used (in total), reduced or disconnected.
64	Consider whether a source of priority 9 must be used (in total), reduced or disconnected.
65	Consider whether a source of priority 10 must be used (in total), reduced or disconnected.
66	Consider whether a source of priority 11 must be used (in total), reduced or disconnected.
67	Consider whether a source of priority 12 must be used (in total), reduced or disconnected.
68	Consider whether a source of priority 13 must be used (in total), reduced or disconnected.
69	Consider whether a source of priority 14 must be used (in total), reduced or disconnected.
70	Consider whether a source of priority 15 must be used (in total), reduced or disconnected.
71	Consider whether a source of priority 16 must be used (in total), reduced or disconnected.
72	Consider whether a source of priority 17 must be used (in total), reduced or disconnected.
73	Consider whether a source of priority 18 must be used (in total), reduced or disconnected.
74	Consider whether a source of priority 19 must be used (in total), reduced or disconnected.
75	Consider whether a source of priority 20 must be used (in total), reduced or disconnected.

Table A.1: Internal clock increments between grid states and associated tasks (Continued)

Counter	Task executed by the 'T'-component on a given time step.
76	Consider whether a source of priority 21 must be used (in total), reduced or disconnected.
77	Consider whether a source of priority 22 must be used (in total), reduced or disconnected.
78	Consider whether a source of priority 23 must be used (in total), reduced or disconnected.
79	Consider whether a source of priority 24 must be used (in total), reduced or disconnected.
80	Consider whether a source of priority 25 must be used (in total), reduced or disconnected.
81	Consider whether a source of priority 26 must be used (in total), reduced or disconnected.
82	Consider whether a source of priority 27 must be used (in total), reduced or disconnected.
83	Consider whether a source of priority 28 must be used (in total), reduced or disconnected.
84	Consider whether a source of priority 29 must be used (in total), reduced or disconnected.
85	Consider whether a source of priority 30 must be used (in total), reduced or disconnected.
86	Consider whether a source of priority 31 must be used (in total), reduced or disconnected.
87	Consider whether a source of priority 32 must be used (in total), reduced or disconnected.
88	Consider whether a source of priority 33 must be used (in total), reduced or disconnected.
89	Consider whether a source of priority 34 must be used (in total), reduced or disconnected.
90	Consider whether a source of priority 35 must be used (in total), reduced or disconnected.
91	Consider whether a source of priority 36 must be used (in total), reduced or disconnected.
92	Consider whether a source of priority 37 must be used (in total), reduced or disconnected.
93	Consider whether a source of priority 38 must be used (in total), reduced or disconnected.
94	Consider whether a source of priority 39 must be used (in total), reduced or disconnected.
95	Consider whether a source of priority 40 must be used (in total), reduced or disconnected.
96	-
97	-
98	Determine demand zones and update demand values in load signals to reflect out-zone sources.
99	Update stored energy quantity inside energy storage element. (Reduce the energy level if has discharged energy or increase the energy level if it was charged with energy.)

A.7 Fault Simulator Model

Consider figure A.17 showing a 'Fault Simulator' function block used in the simulation of the 'T'-Smart grid in Chapter 5.

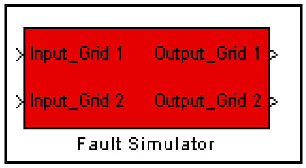

Fig A.17: Simulink representation of the 'Fault Simulator'

Future grids, as the 'T'-Smart grid will have to detect faults and take the necessary action to ensure grid stability and supply to all loads, automatically. In order to better describe and demonstrate this feature, a 'Fault Simulator' function block is introduced to break network connections, without prior warning, to analyse how the grid performs and solves the network and energy constraints as explained in Chapter 4 and simulated in Chapter 5.

The internal model layout of the 'Fault Simulator' function block of figure A.17 is given in figure A.18.

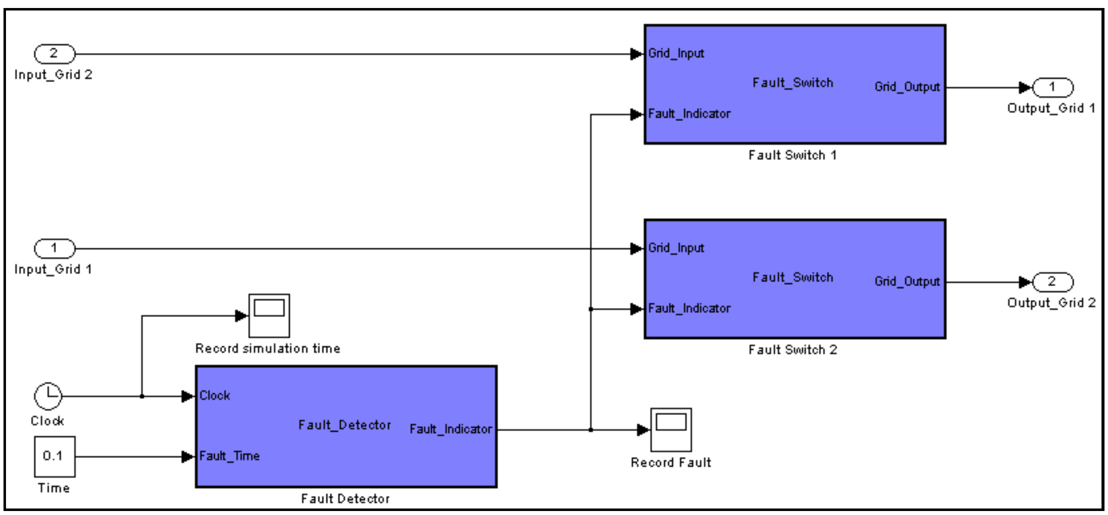

Fig A.18: Internal model layout of the 'Fault Simulator' function block

The 'Fault Simulator' function block is connected in series between two 'T'-components and the communication between these components has to pass through the 'Fault Switch' function block (figure A.18).

The 'Fault Switch' function block, allows all communication to pass through it, until it receives a signal from the 'Fault Detector' function block (figure A.18). Once this signal is received, the communication between the 'T'-components is cut-off and the 'Fault Switch' function blocks simply substitutes empty variables (i.e. '[0 0 0 0 0]') for the communication vector (A) in both directions of communication.

The 'Fault Detector' function blocks emulates a fault in the system, and sends a fault signal to the 'Fault Switch' function block at a predetermined time. Hence, the input to the 'Fault Detector' function block is the simulation time, and the 'Fault time' at which the fault signal must be sent to the 'Fault Switch' function block to stop communication and simulate a break in the network.

Although this is not a component of the 'T'-Smart grid, it greatly assists in showing the method and action taken by this grid under emergency conditions as can be seen in Chapter 5.

A.8 CONCLUSION

This appendix described the models created in (Matlab) Simulink to test the 'T'-Smart grid, as simulated in Chapter 5. This Appendix Aimed at giving the reader insight into how the 'T'-components, Grid-components, and fault simulator component is modelled, functions and internally managed to achieve the results shown in Chapter 5.

In addition, a five parameter communication vector sent between 'T'-components and two four parameter communication vectors sent between 'T'-components and Grid-components was proposed to significantly limit the information being communicated in a future Smart grid. This then leads to a lower telecommunication infrastructure requirement to achieve all the required functions of a future Smart grid.

Another important observation is that the FCL not only limits fault current amplitudes and fault propagation, by it also turns the management of the grid into a discrete system whereby the grid has a fixed amount of time to solve itself before action is required. (Energy is stored and load requests are halted, for a short period, to achieve this. Consider Chapter 4 for more information.) Hence, there is never an unforeseen connection or disconnection (apart from faults) in the system which enables far superior management of the grid.

The 'T'-Smart grid also allows sources to be aware of when grid interventions occurred (if the Grid-operators want to reward the sources functioning in these periods), how load zones (for SNC charges) can be calculated and a proposal was also made how to manage energy storage elements such that network instability and unnecessary switching is reduced. (Consider Chapter 4 for more information.)

Finally, it was also shown that the 'T'-Smart grid can support sub-grids connecting to main-grids, and as explained in Chapter 4, and how these grid levels can almost extend indefinitely due to the system used of reducing a sub-grid to a single lumped source or load. (Consider Chapter 4 for more information.)

APPENDIX B: SAUPEC 2011 PAPERS

This appendix contains two discussion papers presented at the SAUPEC 2011 conference.

A DISTRIBUTED POWER GRID VIA A THREE PORT POWER TRANSFER COMPONENT

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Abstract. The novel 'T'-Smart grid is presented which through the use of a three port power transfer component ('T'-component) is able to seamlessly integrate distributed sources, loads and energy storage elements (grid components) and effectively communicate their respective priorities, total grid demand and network limitations to all customers (and grid components) connected to the gird in order to develop energy markets, ensure economic growth, reduce peak demand and promote the use of renewable resources. The overview of a smart grid that could achieve this is presented in this paper.

Key Words. Smart Grid, 'T'-Smart grid, 'T'-Component.

1. INTRODUCTION

In recent years the evolution of the grid has become a high priority for utilities. Future grids must move away from being a centralised and producer controlled to one that accommodates distributed resources and is consumer interactive to ultimately ensure economic and environmental sustainability.

Future Grids as reported by [1] must have a number of attributes and are ideally: intelligent, efficient, accommodating of different sources, encouraging consumer and utility interaction and communication, exploit markets and opportunities, focussed on quality of supply and security thereof, resilient against attack, self healing and environmentally friendly.

In order to achieve these attributes it is envisaged that the future grid will need to develop such areas as: integration of communication, advance sensors and measurements systems, advanced components, highly developed control methods, robust and enhanced interfaces. These technologies will enable the grid to be reliable, affordable in terms of its infrastructure, economically competitive (globally), fully accommodating of renewable and tradition sources, produce fewer carbon emissions and improve overall efficiency.

It is envisaged that these and other requirements can be met through the implementation of a novel three port power transfer component presented in this paper. This power transfer component is referred to as the 'T'-Component. Several of these components together would form the 'T'-Smart Grid. Integration of sources, loads and energy storage elements (Grid Components) for residential customers through this method would be effortless and seamless without the need of complex setups, frequent maintenance, expensive grid infrastructure, and constant remote control function(s) and interaction.

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This power transfer component will also incorporate a new protection method between grid components and also lower fault levels (Section 2.2). It will also allow for Time-Of-Use metering and tariffs to reduce peak demands and also update the residential customers of this in real time.

The 'T'-Smart Grid still has a SCADA type system referred to as the Control Component to override the system, enable specific grid connections and contingencies, run off-line function(s), and monitor overall health of the grid.

2. T-COMPONENT

The 'T'-Component is a three port power transfer component allowing for inputs/outputs on all three ports of which two are connected to the grid and the remaining port is connected to a customer. The customer may be any type of grid component or a completely new sub-grid comprising of another 'T'-Smart Grid. This is illustrated schematically in Fig. 1.

The 'T'-Component operates by a fixed set of rules which allows it to manage grid components (sources, loads and energy storage elements) and communicate priority and demand measurements (to customer meters) instantaneously. The component rules and pre-programmed control functions also ensures the system functions in a predictable manner under normal conditions with no human interaction required. It is envisaged that this setup alone will replace conventional (distribution) stations and switching stations. The T-Component shall mange the quantity and time when grid components supply, use or store energy.

2.1 'T'-Component properties

Over and above the requirements listed in section 1 [1], the 'T'-Component will have the following properties as a minimum:

- ✓ Prevent fault current propagation.
- ✓ Limit fault levels to reduce grid infrastructure and earthing infrastructure requirements.

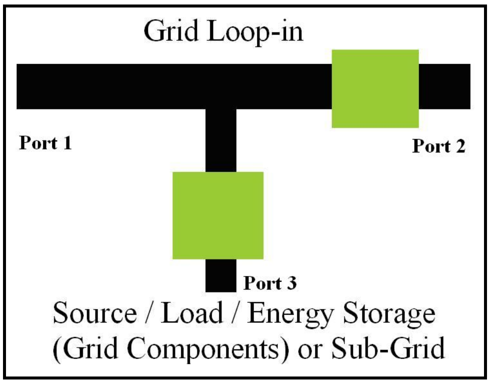

Fig. 1: 'T'-Component connection ports

- ✓ Ensure seamless integration between grid components.
- ✓ Convert electrical signals to and from grid components to be compatible with standard voltages(s) and frequencies(s) of the 'T'-Smart grid. (This will ensure smaller sources are able to feed larger loads under contingency.)
- ✓ Have a common protocol between 'T'-Components, Grid Components, Control-Components and Customer interface units.
- ✓ Relay instantaneous grid parameters to the customer such as the total available energy on the grid, total connected load, infrastructure limitations, grid demand taking into consideration grid infrastructure limitation(s), priority of grid components, etc.
- ✓ Be able to perform self diagnostics continuously and disconnect from the grid if internal malfunction is sensed. (It can make use of differential protection to detect internal faults.) In addition, it should alert both the Control Component and those responsible for maintenance of the infrastructure.
- ✓ Monitor and sense temperature and current flow in conductive mediums connected to it, to determine and update the medium's maximum power transfer capabilities in real-time to the grid and its components. (This will allow safe overloading under emergency conditions or where cyclic loading occurs.) It should also detect and report hot-spots and other abnormalities on the installation and report it to the Control Component.

2.2 Internal layout

The 'T'-Component comprises of several sub components of which the 'Fault Current Limiter' (FCL) is the most significant. It prevents fault current from propagating and reduces fault current amplitudes. (These FCLs are indicted by the *green* blocks on Fig. 1.)

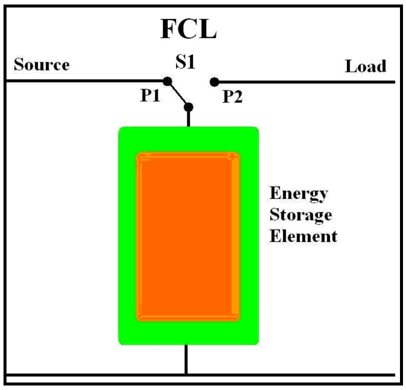

Fig. 2: Fault Current Limiter (FCL)

The functioning of the FCL is best illustrated in Fig. 2. The main function of the FCL is to store energy from a source in a temporary energy storage element when switch S1 is in position P1. Once fully charged, it discharges to a load or a subsequent 'T'-component when switch S1 is moved to P2. The cycle is repeated continuously.

By doing so the fault current amplitude is limited to the size of the energy storage element. (Increasing the switching frequency of T1 will also allow for a smaller energy storage element which will lead to an even lower fault level.) Also, the 'T'-Component can sense the rate at which the energy storage element inside the FCL charges and discharges, to so detect a fault and disconnect to stop its propagation. (Note that conventional protection such as Impedance-, earth fault- and differential- protection may still be present in the 'T'-Component as well). While an explicit source and load is shown in Fig. 2, the FCL is completely bi-directional in nature.

The reduction of fault levels also decreases the earthing infrastructure (earth rods, earth mats, surge arrestors, etc.) which can be costly and is only utilised under fault conditions.

If two FCL's are connected in parallel (Fig. 3) so that when the energy storage element connected to S1 is discharging through P2, then the source can charge the second energy storage element of S2 through P3. Once the first energy storage element is fully discharged, the circuit will switch back to charge it again, while the second energy storage element discharges. If multiples of FCLs are connected in parallel, then signals of different amplitude and frequency can be created by varying the frequency and duty cycle of the switches.

Hence, any section of the grid between two 'T'-Components or 'T'-Components and grid components can be seen as a (limited) source connected to a conductive medium and a load. (Note that these energy storage elements in the FCL are not bulk energy storage elements. They should not be confused with externally connected bulk energy storage to manage peak demand.)

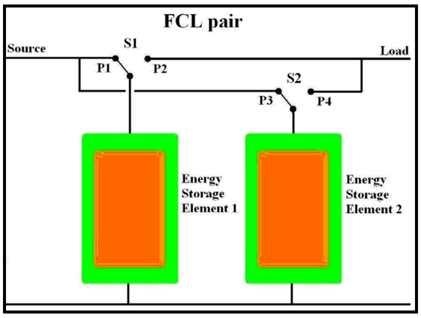

Fig. 3: FCL pair with S1 and S2 operated out of phase.

This solution also provides an isolated connection between the 'T'-Smart grid, and conventional grid infrastructure.

The 'T'-Component communicates with a Control Component and other 'T'-Components through the internal 'Control and Communication' component as seen in Fig. 4. Information that is communicated includes energy flow, grid configurations, faults, general metering, etc.

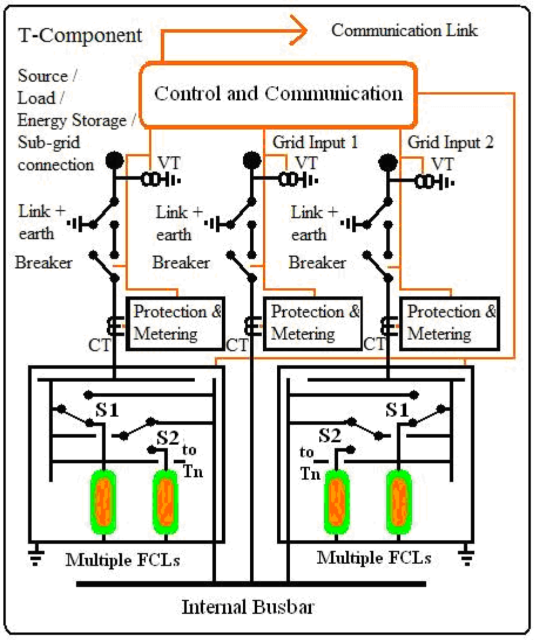

Fig. 4: Internal layout of 'T'-Component with multiple FCL sets

2.3 Priority assignments to Grid Components

In the 'T'-Smart Grid all grid components are assigned priorities. (The 'T'-Smart grid is managed based on a prioritisation structure. Sources, loads and energy storage elements with the highest priority are considered and solved first before the remainder of the grid's components.)

The priority of a particular source is determined by the quantity of energy it can generate, the time (availability) and duration of generation, environmental impact, network length to load centres (loss calculation and infrastructure requirements), economic sustainability, etc. A unique priority is assigned to each source.

The priority of a load is dependent on the quantity of energy it uses, the time and duration of usage, environmental impact, network length to load centres (loss calculation and infrastructure requirements), load types (Critical: Example lights, heat, security. Non-critical: Example entertainment and loads that can be shifted to low peak times such as cleaning and washing machines.), etc. Priority values however are not unique. Hence loads (and load types) are grouped together and will be shed together if there is insufficient generation capacity.

Energy storage elements can be a source or load, depending on what is required by the grid. It is assigned a unique priority due to its unique ability to change between two different modes of operation (load and source).

Grid priorities are set up initially, but can later be altered by the Control-component to improve security of supply and grid performance based on off-line programs with optimisation algorithms or user override.

The debit bill for loads (and when energy storage elements are charging) will consist of the quantity of energy used and time of usage, the pro-rata priority value of source(s) it was supplied by as well as the grid demand and grid zone value discussed in the next section (Section 2.4).

The credit bill for sources will consist of the of the quantity of energy generated and time of generation, the priority value of source(s), as well as the grid demand at the time of generation.

All this will be summarised and included in one bill to the customer.

2.4 Demand zone(s) and demand categorisation for loads

Time-of-use tariff and metering is considered a powerful technique to reduce loading in peak-time.

In addition to billing a customer for the instantaneous demand the grid is experiencing, a cost for the infrastructure use must also be added. Conventional metering has a Shared Network Cost (SNC), but this parameter will vary in a grid with distributed sources. The demand zone parameter assigned to loads is a possible solution to address this.

These demand zones are predefined areas (number of up-stream / down-stream nodes, or network length) in which sources can supply the load and be considered 'In-zone'. Beyond this is considered 'Out-zone'. (Many zones may be defined but are limited to only these two for purposes of this paper.)

An additional cost will also be levied if a load is supplied by load-shedding another load or purchasing power from a neighbouring grid. This is referred to as an intervention and load accounts would reflect this as well.

The actual demand value assigned to a load meter is between 0 and 1 (i.e. 0% - 100%). However, based on the above, this value is incremented to fit in the correct category as seen in Table 1.

Table 1: Demand Categories

0 <= Demand <= 1	In-zone	Load supplied
1 < Demand <= 2	Out-zone	Load supplied
2 < Demand <= 3	In-zone	Load supplied with intervention
3 < Demand <= 4	Out-zone	Load supplied with intervention

2.5 Energy Storage element's Modes of operation

Energy Storage elements intelligently interact with the 'T'-Component and can either be connected between a source or load and the 'T'-Component, or on its own. When connected between a source and a 'T'-Component, the energy storage element stores energy not used by the grid. This then increases the source's supply capacity. The energy storage element loses its unique priority in this operation and takes on the one of the source.

If the energy storage element is connected between a load and a 'T'-component, it draws a constant energy charge from the grid and supplies the load which may have unpredictable low and high loading peaks. The rate at which energy is stored can be determined by neutral networks, adaptive filtering, or similar technology that studies the customer's loading habits and ensures that energy is always available, while still drawing a constant energy profile from the grid. (A reasonably sized energy storage element would also be required to achieve this.) Again, the energy storage element loses its own priority and takes on the one of the load in this operation.

The final mode of operation is if the energy storage element is connected to the grid on its own (through a 'T'-component), and stores excess energy and discharges when there is a shortfall. The energy storage element has its own unique priority when managed in this operation, as discussed in section 2.3.

If the energy storage element is functioning in the final mode of operation, the charging of the energy storage element doesn't affect the grid's demand as this energy would have been lost if not stored. However, it does impact the grid's demand when it discharges and it is modelled as a source. (This operation will be most beneficial if energy storage element(s) are placed at strategic points in the network, to alleviate infrastructure upgrade due to peak loading.)

An energy storage element can also be connected to a 'T'-component in a sub-grid and set to the final mode of operation. Then it will only meet the requirement of the sub-grid and so customers can use excess energy generated by their sources only for their own purposes and not sell it to the grid.

2.6 'T'-Smart grid management process

Consider Fig. 5 showing three 'T'-Components in a main grid (T1, T2 and T3) and two T-components (T1 (sub) and T2 (sub) connected in a sub-grid. The sub grid can be reduced to a load or a source connected to T2, depending on which is the largest. Also, taking into account on the quantities of energy and grid component's priorities involved, the main-grid and sub-grid will solve itself simultaneously in adherence to the fixed set of rules depicted in the flow chart of Fig. 6.

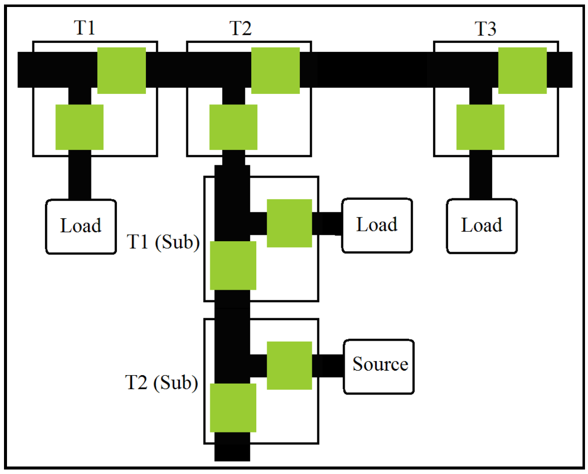

Fig. 5: Typical 'T'-Component smart grid

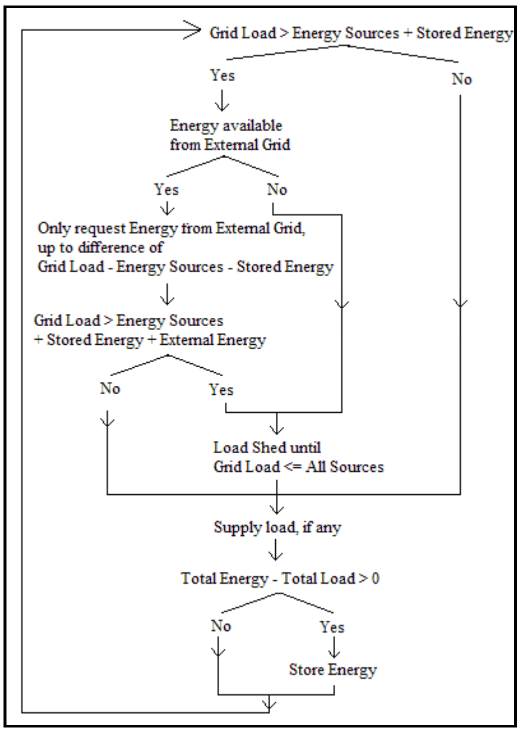

Fig. 6: Grid Management Process for a Main-grid or Sub-grid

3. CONCLUSION

A 'T'-Smart Grid comprising of 'T'-components was presented in this paper which is aimed at ensuring customer interaction, economic growth through energy trading and distributed renewable energy generation. While at the same time still maintaining a fully protected network which limits fault levels, considers higher priority energy sources first and allows for the automatic charging and discharging of energy storage elements in low-peak and high-peak times to manage demand loading.

The 'T'-Smart grid is also intelligent and fully automated including network switching under fault conditions, and is able to manage and control any source, load and energy storage element. Together with relaying information to the customers about the priority of sources and loads, external demand of the grid and the network's infrastructure constraints, the system will promote and develop markets never experienced before where customers and utilities can engage in energy trading. This system can also reduce the need to upgrade networks as sources and loads are effectively moved closer together in a distributed system.

This is achieved through the implementation of universal 'T'-components which connect to other 'T'-components and grid components to ultimately meet all the requirements of a smart grid and those mentioned in section 2.1

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[1] U.S. Department of Energy, "The Smart Grid: An Introduction.", Online Paper: http://www.oe.energy.gov/DocumentsandMedia/DOE_SG_Book_Single_Pages.pdf

A DISTRIBUTED POWER GRID VIA A THREE PORT POWER TRANSFER COMPONENT – SIMULATED IMPLEMENTATION

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Abstract. A novel Smart Grid solution based on a novel 'T'- component has been presented and promises good performance especially in a situation where there is a lot of distributed generation. In this paper the new type of mart grid is evaluated by means of a small scale simulation. The details of the simulation are presented generically for several grid events. The results show complex but predictable behavior.

Key Words. Smart Grid, 'T'-Component, Distributed generation, Simulated 'T'-Smart Grid

1. INTRODUCTION

A smart grid system using a three port power transfer component has been proposed and an operational overview has been presented in [1]. This smart grid system is now modeled and simulated using Simulink in a practical example. This paper only focuses on the presentation of results from the simulation. Some of the details of the approach are omitted due to the scope of the paper. These details are given in [1].

2. EXAMPLE 'T'-SMART GRID

Consider Fig. 1, which shows a radial connected network of five T-components named T1-T5. This example network connects three types of loads and two types of sources, interconnected as shown.

All the T-components are setup to have an infinite busbar/grid capacity, except for T3 which is limited to 70 units of energy. Similarly, the input Fault Current Limiter (FCL) limit for all the grid components is set to infinite, except for T2 which is limited to 140 units of energy. (Practically, the input FCL limit should always be less than the limit of the busbar/grid. These settings were only chosen for illustration purposes.)

The demand in-zone for all the T-components is also set to one T-component above, and one T-component below. Any load being supplied from any source that is further away than stated above, will be considered out-of-zone.

The load requirements that the loads have communicated to their respective T-components over time is shown in Fig. 2. As shown in the figure, loads 1 and 3 request a constant energy profile (both 60 units of energy) while load 2 has an incremental step of 20, 80 and 140 energy units every second and then it repeats this cycle. Note that in this example, the loads do not change their priority. Their priorities are 10, 15 and 5 for loads 1, 2 and 3 respectively.

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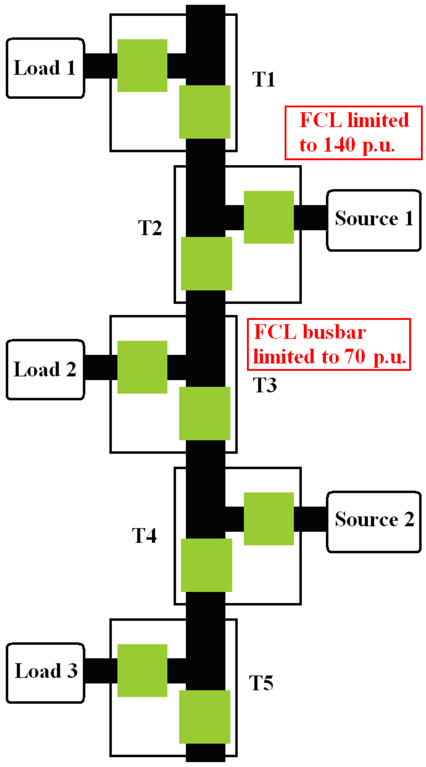

Fig 1: Radial connected, five T-component smart grid.

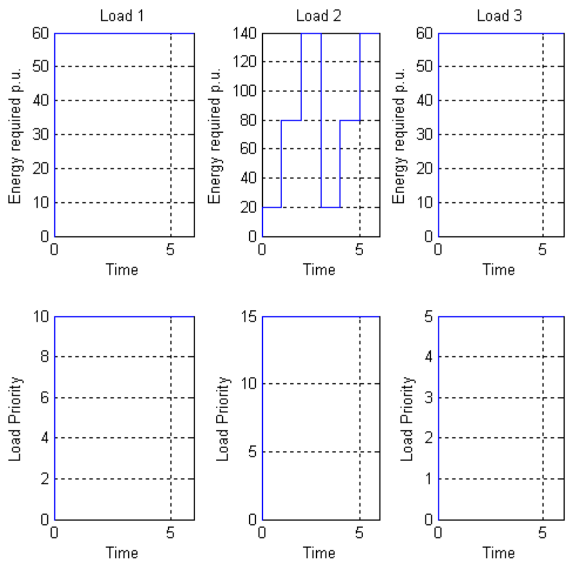

Fig 2: Loading requirements of Loads 1, 2 and 3 for 6 seconds.

Now consider the available energy of the sources depicted in Fig. 3, which was communicated to their respective T-components.

As shown in Fig 3, source 2 can deliver 80 units of energy at a constant rate over 6 seconds while source 1 can deliver 120 units of energy for the first 3 seconds and then 160 units for the remainder of the time. (Again, their priorities remain the same for this example. Their respective priorities are 20 and 10 for sources 1 and 2 respectively.)

Note that both the energy generated by the sources, and requested by the loads, are distributed in the grid over 1 second intervals (shown at the top of figure 2 – 5) which can also be viewed as representing the apparent power generated and used.

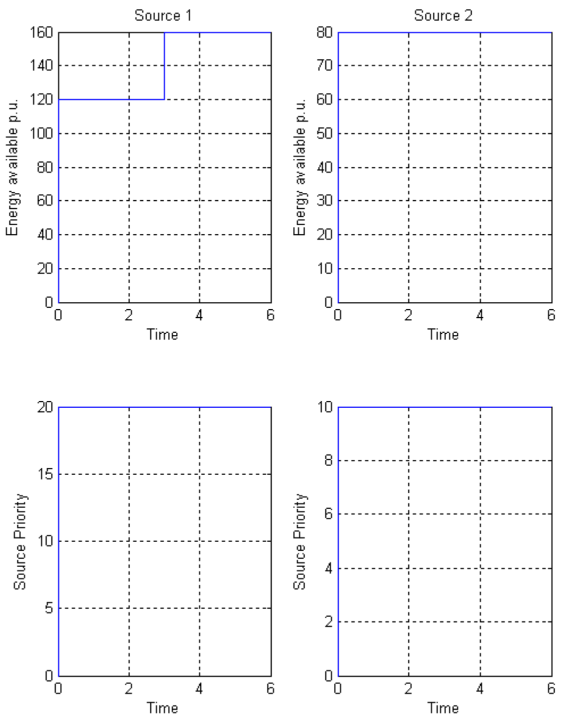

Fig 3: Energy made available to the grid by sources 1 and 2 over 6 seconds.

These settings and parameters are configured in a Simulink simulation and the results obtained are shown in Fig. 4 and Fig 5.

Consider Fig. 4, the first column which indicates the energy distributed to the first load.

The first load received its requested 60 units of energy constantly through out the simulation of 6 seconds from source 1 which is closest to it, except for the period between 2 – 3 seconds where it was shed.

During period 2 – 3 seconds, the total load in the circuit was 60 (load 1), 140 (load 2) and 60 (load 3) units of required energy while there where only 120 (source 1) and 80 (source 2) units available. Hence, load 3 would have been shed, because it is the lowest priority, so that the total load would be 140 + 60 = 200 energy units required and the total source would be 120 + 80 = 200 available energy units.

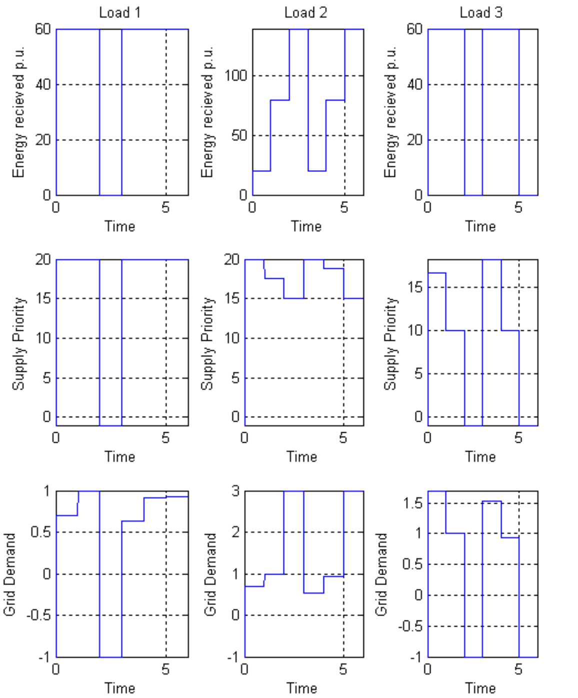

Fig 4: Energy distributed to Loads 1, 2 and 3 by the T-component Smart grid

However, the third T-component (T3) has a limited busbar of 70 units of energy. Hence, it can only receive 70 units of energy from above and 70 units of energy from below to supply the highest priority load in the circuit. Hence, source 2 supplies it with 70 units of energy from below and source 1 supplies it with 70 units of energy from above. Thus, source 2 only has 10 units of energy remaining which is insufficient to supply load 3 and source 1 has 50 units of energy remaining which is insufficient to supply load 1. (Note that Load 1 and Load 3 had a lower priority than load 2; load 3 was shed first and then load 1 in order for the grid to supply load 2.)

For the time that the load had supply, the supply priority was 20 as seen in Fig. 4. This is because throughout the simulation it was supplied by its closest source, source 1 which had a priority of 20. Note that in the period 2 – 3 seconds when the load was shed, its displayed priority is -1, so that it can not be confused with a source with a supply priority of zero. All load and source priorities have positive integer values.

Its demand between period 0 – 1 second is the same as the remainder of the grid at 0.7 because there are 120 energy units available from source 1 and 80 energy units from source 2. Also, for the first second the loading requirements for loads 1 to 3 are 60, 20 and 60 energy units. So the demand is (60 + 20 + 60) / (120 + 80) = 0.7.

Between seconds 1 and 2, the demand becomes 1 as the second load requires 80 units of energy. So, (60 + 80 + 60) / (120 + 80) = 1. After this, between second

2 and 3, the demand is -1 because the load was shed. (Again, '-1' is chosen as a unique value to show the load was shed and not '0' which can be confused with a grid that has an infinite large source and/or infinite small load.)

The demand for the remaining period of load 1 was 0.636, 0.909 and 0.929 for seconds 3 to 4, 4 to 5 and 5 to 6 respectively. The reason for this is that source 1 has made 160 units of energy available, which is 40 energy units more than the first 3 seconds. However, the FCL (of T2) could only transfer 140 units of that energy as stated initially, to the network. Hence, (60 + 20 + 60) / (140 + 80) = 0.636, (60 + 80 + 60) / (140 + 80) = 0.909 for the period 3 to 4 seconds and 4 to 5 seconds.

For the period 5 to 6 seconds, the circuit had a total load of (60 + 140 + 60) required units of energy and a total source of (140 + 80) of available energy units. Hence, the loading exceeded the available source energy and Load 3 was shed, due to it having the lowest priority as seen in the last column of figure 2 and 4. Now, because the FCL busbar limit of T3 is limited to 70, independent of what is connected to T3 to T5, the amount of energy that can be transported to T2 and T1 can never exceed 70 units of energy nor can it request more than 70 units of energy.

Hence, in this case, because of this limitation, the total energy requested from source 1 on the side of the grid where source 1 and load 1 is located, was 70 units of energy from T3 and below. Thus, the demand is (60 + 70) / (140) = 0.929. (Note that as soon as load 3 was shed, energy of source 1 and source 2 was sent to load 2 and then the network limitation of T2's busbar was noticed by the grid, and hence taken into account. Thus, in this model, the maximum network capability affects the demand, but only when maximum network capacity is reached. Also consider the demand on load 2 in this same period and the period 2 – 3 seconds in Fig. 4, later.)

For the moment we will consider the third load before coming back to the second load. It can be seen in Fig. 4 that it only receives its required energy for the period 0 to 2 seconds and 3 to 5 seconds, and it shed during period 2 to 3 and 5 to 6 seconds. In the period 0 to 1 seconds, its supply priority is 16.667. The reason for this is that the source 1 and has spent all of its energy on load 1 and load 2, and that the remaining energy had to be combined with source 2 to supply load 3. (Note that source 1 is used to supply the grid first, before source 2 because it has a higher priority.) Hence, after supplying load 1 and load 2, it only had 120 – 60 – 20 = 40 units of energy available. The load requested 60 units of energy, of which 40 units will come from source 1 and 20 units from source 2. Applying a pro-rata calculation, the supply priority to the load is 40/60 * (20 – supply priority of source 1) + 20/60 * 10 (10 – supply priority of source 2) = 16.667. For the period 1 to 2 seconds, source 1 supplies load 1 and a portion of load 2. Source 2 then supplies the remaining required portion to load 2 to and fully supplies load 3 at a priority of 10 as seen in Fig. 4.

For the period 2 to 3 seconds and 5 to 6 seconds, the supply priority to load 3 is -1 because this load is shed during this time. In the period 3 to 4 seconds, the supply priority would have been 20 because source 1 is able to supply all the loads in the network. However, because of T3's limitation, it can only supply 70 units of energy (of which 20 units will be used by the load connected to T3.) Hence, the supply priority is 50/60*20 + 10/60*10 = 18.333.

In the period 4 to 5 seconds, the same happens as in the period 1 to 2 seconds and the load is supplied by only source 2.

The demand of load 3 is 1.7 and 1 for the period 0 to 1 seconds and 1 to 2 seconds. Note that the demand of 1.7 is equivalent to the demand of 0.7 experienced in the same period by load 1. The only reason that it is incremented by 1 is that it is supplied by a 'out-of-zone' source, as it was previously set that only a single T-component directly above or below to where it connects to, would be considered 'in-zone'. (Note that only a portion of the power [source 1] was further than one T-component away and this alone triggered the 'out-of-zone' demand. - Also note how it was possible for source 2 to supply load 3 alone, which would then result in a 'in-zone' demand.)

For the period 1 to 2 seconds, the demand is the same as load 1 at a demand value of 1 because the total available energy matches the total load requirements of the grid exactly. The demand value is not incremented as it receives its total supply from source 2 which is 'in-zone'. As for the period 2 to 3 seconds and 5 to 6 seconds, the demand is -1 to signify that the load was shed.

For the period 3 to 4 seconds, the limit of T3 again plays a role and limits the energy from T2 through T3 to 70 units. Hence, the demand on the side of T4 to T5 is (20 + 60) / (70 + 80) = 0.534. It is now just incremented for the fact that source 1 is 'out-of-zone' to it. (Hence, 1.534) As for the period 5 to 6 seconds, the demand is (80 + 60) / (70 + 80) = 0.934 and it was supplied by an 'in-zone' source.

Load 2 is supplied for the entire 6 seconds of the simulation due adequate source and network capacities, and the fact that it has the highest priority. In the period 0 to 1 seconds and 3 to 4 seconds, source 1 supplies it at a priority of 20 without any difficulty. Once the period 1 to 2 seconds is reached, 60 units of energy are supplied by source 1 and 20 units of energy by source 2. Hence, 60/80*20 + 20/80*10 = 17.5. For the period 2 to 3 seconds and 5 to 6 seconds, 70 units of energy is supplied by source 1 and 70 by source 2, which means that supply priority will be 15. Finally, for the supply period of 4 to 5 seconds, the value would be 70/80*20 + 10/80*10 = 18.75.

The demand is exactly the same for load 2 as for load 1 and load 3 in the period 0 to 2 seconds for the reasons previously discussed. In the period 2 to 3 seconds, load 1 and load 3 was shed and source 1 and source 2 had to supply load 2. Thus, (140) / (120 + 80) = 0.7. However, the energy being supplied reached the busbar limit of T3 and hence, the demand became 1. (The argument is that the demand will always be represented by the limiting component whichever is the smallest between the source and the network capacity.) This value is then incremented by 2, as loads 1 and 3 where shed which counts as an intervention.

For the period 3-4 seconds and 4-5 seconds, the demand is again limited by the busbar capacity of T3 and thus the demand would be (20 + 60) / (70 + 80) = 0.534 and (80 + 60) / (70 + 80) = 0.934 respectively. (Note that source 1 can only supply the portion of the grid from T3 to T5 with a maximum of 70 units of energy.) In period 5 to 6 seconds, load 3 was shed which made the demand (60 + 140) / (120 + 80) = 1. However, an intervention occurred and it was incremented by 2 to equal 3. (Note that in actual fact, the demand of load 3 is also unity because the busbar of T3 reached is maximum capacity. Hence, even if the available energy of source 1 and source 2 where increased, the demand value would have remained the same.)

Consider now Fig. 5. As can be seen in the first column, source 1 supplied 120 units of energy in the period 0 – 2 seconds, then 70 units in the period 2 – 3 seconds, and 130 unit of energy in the period 3 – 6 seconds which is consistent with what was discussed earlier. Its supply priority remained the same at 20 throughout the simulation as it was set to be constant.

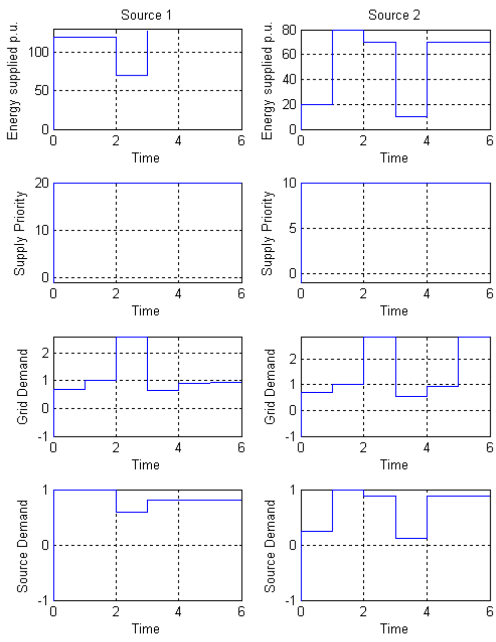

Fig. 5: Energy supplied by source 1 and source 2 in the T-component smart grid

Next, the sources have their measurement of the grid demand which they can use to determine when to sell their energy and so be more profitable. Except for the period 2 – 3 seconds, the grid demand of source 1 is exactly the same as for load 1, because of T3's limited busbar capacity which splits the grid demand into different values at different places in the grid.

The only reason why it differs in the period 2-3 seconds is because during this time, load 1 was shed, and source 1 could only deliver 70 of its 120 units of available energy which meant that this portion of the grid had a grid demand of 70 / 120 = 0.583. However, this value was incremented by 2, as the source was aware that a load shedding intervention had occurred.

In addition to the grid demand, sources have an internal demand that varies between 0 and 1 when supplying load, which is used for maintenance and planning purposes to the owner of the source. This value is simply calculated as the amount of energy the source supplied to the grid, divided by its own maximum capacity. For the period 0 – 2 seconds, it supplied all of its available energy and its internal demand was 120 / 120 = 1. For the period 2 – 3 seconds, the demand was 70 / 120 = 0.5833 due to busbar limit of T3. Finally, for the period 3 – 6 seconds, it could supply 160 units of energy, but the T2's FCL limit was 140 units. In addition to this limitation, again the busbar of T3 limited the transfer capacity to 70 which meant the source could only supply 130 units of energy during this time. (60 units of energy where supplied to load 1.) Hence, its internal demand is 130 / 160 = 0.813. (Note that this is value is computed by the source itself and not by the T-components.)

For source 2, because it has a lower priority than source 1, it only supplied energy when source 1 couldn't meet the loading requirements or where network capacity prevented source 1 from doing so. So, it supplied the T-component grid with 20, 80, 70, 10, 70 and 70 units of energy over each second of the simulation. Adding these values to what source 1 supplied, the total amount of energy supplied was, 140, 200, 140, 140, 200 and 200 for each simulated second which is consistent with the loading requirements of the grid for each period. Its supply priority remained constant at 10 throughout the simulation.

The grid demand of the source 2 was exactly the same as for load 3, except for the period 2 – 3 seconds and 5 – 6 seconds when load 3 was shed. This is due to the fact that source 2 and load 3 is located under the same network capacity constraints. Consequently, this demand is not only consistent with that of load 2 but also differs in the period 2- 3 seconds and 5-6 seconds due to load 2 requesting energy coinciding with T3's maximum capacity. (Note that the grid demand for sources is only incremented for interventions, and not for 'in-zone' or 'out-of-zone' scenarios as it is supplying the energy.)

For the period 2-3 seconds, the total load was 70 units of energy towards load 2 and the total amount of energy available was 80 (source 2), thus 70/80 = 0.875. This value is incremented by 2, due to the load shedding intervention of load 1 and load 3.

From the perspective of source 2, in the period 5 – 6 seconds, it still only supplies 70 units of energy to T3 which has a limited busbar capacity of 70 units. Hence, its demand remains the same as for the period 2 – 3 seconds. (Thus, 70/80 =0.875 + 2 because load 3 was shed.)

Finally the internal source demand is again equal to the amount of energy supplied divided by its maximum capacity. Hence, 20/80 = 0.25, 80/80 = 1, 70/80 = 0.875, 10/80=0.125, 70/80=0.875 and 70/80=0.875 over each of the simulated seconds.

3. CONCLUSION

This paper presented a practical scenario of a radial connected network of two sources and three loads, through the use of T-components of T-Smart grid system. A detailed description was given of the operation of the each component during several grid events, generation- and load-changes.

The behaviour shown is relatively complex and indicated that as the size of the network grows, planning may be difficult due to the unpredictable behaviour of the load demands. It has been shown that on a small scale the grid can be well behaved. However larger scale simulations are still needed to be able to fully illustrate the benefits of the 'T'-component smart grid.

REFERENCES

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