

Realisation of Ad Hoc Renewable Rural Power Systems

with Decentralised Active Power Dispatch Techniques



Jarren Hilton Lange

Faculty of Engineering and the Built Environment
University of Witwatersrand

This thesis is submitted for the degree of
Doctor of Philosophy

To my parents, family and friends...

Declaration

I, Jarren Hilton Lange, declare that this thesis is my own, unaided work, other than where specifically acknowledged. It is being submitted for the degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed:

Jarren Hilton Lange
8 July 2019

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Abstract

Ad hoc power systems offer a promising opportunity to provide affordable reliable renewable energy to rural areas. Classical grid solutions are impeded by low population densities and poor economic conditions that perpetuate energy poverty in large areas of rural Africa. Existing islanded renewable energy based solutions can not typically be expanded at will as the needs of its users increase. Scalable power systems, that can lower the engineering costs of commissioning and modifying the system represents a potential solution to energy poverty. Existing solutions rely on the ability to tightly model and control all elements a result of the stringent requirements imposed on these systems. Meaning scalable power systems are theoretically unrealisable. Thus, this is a system architecture and control issue, not a generation or storage issue.

This thesis explores ways to realise low cost scalable power systems for low ($> 1 \text{ kW}$) to medium ($< 1 \text{ MW}$) power requirements. Allowing power system parameters to indefinitely deviate from nominal values, which discards a 140 year old assumption, is achievable in new electronic generation based power systems. This allows all system elements to contribute towards system operation without additional communication. Modelling is presented which simplifies complex power interactions in AC systems to passive circuit components. The desired characteristics of each element while utilising existing technologies can be identified from this modelling. These techniques, which are demonstrated and verified on a hardware based power system simulator, enable scalable economically feasible renewable power systems. This provides a novel, flexible and robust alternative to existing power systems that enables the affordable decentralised ownership and operation of renewable power systems at a household level.

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Acronyms

BIBO Bounded Input Bounded Output.

DSP Digital Signal Processor.

EI Eastern Interconnection of the United States of America.

emf Electromotive force.

LPF Low Pass Filter.

PID controller Proportional–Integral–Derivative controller.

PLL Phase Locked Loop.

SoC State of Charge.

ZOH Zero Order Hold.

List of Symbols

C Electrical capacitance.

δ Phase angle between two sinusoidal voltages applied across an element.

D Droop co-efficient.

D_{lin} Linear droop co-efficient.

E_f Internal EMF produced in a synchronous machine.

f_{max} Maximum rated frequency.

f_{min} Minimum rated frequency.

f_g Frequency of fundamental component in an AC grid.

H Mechanical Moment of inertia, units of $kg.m^2$.

V_l Electrical voltage applied to the load.

i_l Electrical current drawn by the load.

I_N Norton current used in Norton modelling.

J Electrical moment of inertia, units of $W.s/Hz$.

k_d Gain of derivative component of PID controller.

k_i Gain of integral component of PID controller.

k_p Gain of proportional component of PID controller.

ω Angular velocity.

ω_{max} Maximum rated angular frequency.

-
- ω_{min} Minimum rated angular frequency.
- ω_0 Nominal angular velocity.
- P_{max} Maximum rated power.
- P Active power.
- P_{in} Active power input.
- P_o Active power output.
- P_0 Nominal active power output.
- Q Reactive power.
- R Resistance or Real component of complex impedance, Z .
- R_f Synchronous machine excitation field winding resistance.
- s_i State indicator, used to map measured indicators to the defined grid state of operation.
- s_l Lower limit of state indicator.
- s_u Upper limit of state indicator.
- τ_{elec} Resultant torque applied by electromechanical elements, electric load on a machine for example.
- τ_{mech} Resultant torque applied by mechanical elements, mainly prime movers.
- T Unit of time.
- V Voltage.
- v_0 Nominal dc voltage.
- V_{ave} average phase voltage.
- V_{exc} voltage applied to machine excitation.
- V_{max} Maximum rated voltage.
- V_{min} Minimum rated voltage.

V_{np} voltage of phase n to neutral.

V_{SP} nominal voltage setpoint.

V_t Terminal voltage of synchronous machine.

X_s Equivalent series impedance of synchronous machines.

X Inductive imaginary component of complex impedance, Z .

Z Complex impedance.

ζ Damping coefficient.

Terms and Definitions

ad hoc Adjective describing something made for a particular need, not planned beforehand.

black start The process of restoring a power system to operation from total shutdown.

blackout Complete grid shutdown.

brownout The drop of grid parameters that may lead to reduced operation but not complete grid shutdown.

load-shedding The controlled rotational disconnection of loads in order to avoid overloading grid generation.

phase locked loop A control system that generates an output signal whose phase is related to the phase of the input signal.

plug and play The ability of a system, or elements of the system, to be used after being added to a system without device configuration or user intervention.

X/R ratio The ratio between the imaginary (X) and real (R) impedance of a power transmission line.

Zero Order Hold Mathematical modelling of signals from discrete-time to continuous-time, by holding each sample for one sample interval.

Chapter 1

Introduction

Electrical power systems first originated for public use in the 1880's, where hydroelectric generation was used to provide power for street lighting. Since then electrical power has become an integral component in the operation and technological development of the world. Electrical energy is a vital component in the way we currently conduct business, provide healthcare and communicate ideas worldwide. A strong correlation exists between the energy consumption per capita and the UN human development index (HDI) of a country especially for energy poor countries. The usage of biomass to meet energy needs has a negative impact on the HDI of a country [1].

However, there still exist areas in Africa which do not have access to electrical energy. For example, in Sub-Saharan Africa only 43 % of the population have access to electricity with a markable difference between urban and rural areas (76 % vs 25 % respectively) [2]. Issues such as low population densities economic hardships and logistic difficulties render existing electrical energy grid solutions incapable of effectively and reliably providing energy to a large population within the African context [2, 3]. Therefore, the planning and design of these systems occurs with vast amounts of uncertainty, leading to either over-engineered and expensive solutions or affordable but inadequate solutions.

It has been noted by Punam Chuhan-Pole, World Bank lead economist: "*Leapfrogging over the traditional stages of national grid-based electrification will require a combination of different systems to answer diverse needs*" [2]. This can refer to the need to reform regulations and rethink how we utilise power systems to reduce the barriers to rural electrification.

Historically grid parameters needed to be tightly controlled for the electromechanical devices used. Issues such as electromagnetic saturation and mechanical resonances strictly limited the operating ranges of power systems. Therefore, historically solutions rely on the ability to tightly model and control all elements. This has lead to the hierarchical approach of

controlling the electrical power system, where a relatively small number of large generators supplied many smaller loads. Communications can be configured between the small number of generators to allow for centralised control. This has largely defined the way in which power systems have been designed and operated. Under this paradigm, freely expandable power systems, that increase as the needs of its users grow, are not possible.

Islanded electrical power grid solutions, that are plug and play and hence expandable, are an attractive option for areas which currently lack existing infrastructure. An islanded power system is a stand-alone electrical grid that relies on localised generation alone to provide the necessary power to supply loads. Thereby negating the costly endeavour of engineering a transmission solution to provide electrical energy over large distances. Due to the relatively small number of loads and generation present in an islanded system, load diversity is low. It is therefore highly likely for these systems to see load changes that can easily exceed the total available generation.

Currently islanded power solutions rely on the establishment of reliable generation. In most cases, this is provided by a diesel generator, which has to remain part-loaded regardless of the availability of renewable sources and be capable of supplying the power requirements of the entire grid. Alternative solutions include the use of batteries to ensure the availability of electrical energy and/or the use of a central controller. Centralised control schemes need to monitor and control all nodes within a network in order maintain a hierarchical power system. The disadvantage of these systems is the lack of flexibility. Once a central controller has been established for a certain power network arrangement further expansion of that power system cannot occur without expert changes to the central controller.

The introduction of ecological and sustainability goals adds further constraints. Popular sustainable sources of generation include solar photovoltaic and wind turbine. Africa experiences high levels of solar radiance compared to other continents making photovoltaic an attractive solution [4]. Despite the large potential for solar energy in Africa, penetration of solar energy is low [5]. Solar based generation tends to be highly stochastic in nature. It is common for solar generation to change from 90% to 10% power output in a few seconds due to changes cloud cover. This adds uncertainty into the operation of these power systems.

Decentralised operation is therefore attractive in this context. The vast amount of uncertainty in the planning and operation of these systems, renders these systems time-variant and hence unsuitable for classical control techniques. Decentralised control is characterised by all active elements in the system making individual decisions towards the control of the entire network. This is inspired by stigmergy, a consensus mechanism whereby individual elements are indirectly coordinated through observations of the environment. A common example

would be the road traffic system, where individual drivers execute actions through local observations of traffic patterns and road rules without the need for a centralised co-ordinator.

The approach taken in this research is to allow the frequency to vary indefinitely from the nominal values by a predetermined amount. In order to allow for scalability, the system needs to operate from a single unit to an unknown number of units. Utilising existing technologies such as droop and inertia (whether virtual or mechanical) the system can be constructed to autonomously dispatch the correct amount of power required, while managing the prioritisation of renewable sources, storage and other nodes. These techniques were validated using a hardware based simulator constructed with commercially available power hardware. This ensured that repeatable validation was performed in the presence of noise, communication delays and other non-ideal equipment behaviour to be expected during implementation and deployment of such a system.

1.1 Research Question

The aim of this research is to be able to bring different techniques together to realise a feasible plug and play power system to be used in ad hoc arrangements. This may require the re-evaluation and re-prioritisation of the electrical power systems.

This leads to the research question to be addressed:

1. What decentralised operations should be implemented in islanded power systems to realise ad hoc operation.
2. What are some limitations and requirements of a decentrally operated island power system.

1.2 Document Overview

The thesis is presented as follows.

Firstly existing literature is presented and analysed in chapter 2. This includes research pertaining to electrical generation, electrical inverter operation, grid control techniques and common terms used.

The basic requirements to create a power system are then re-organized in chapter 3. This presents the basic requirements of any electrical power system and the required actions that all nodes should obey for plug and play operation. This includes the definition of priority

nodes, where certain systems may be granted priority to generate or absorb power over others.

The modelling used to predict the behaviour of islanded power systems is presented in chapter 4. By first examining the similarities between dynamics of a basic DC supply circuit and comparing it to the AC swing equation comparisons can be drawn which allows the dynamics of the AC system to be modelled using passive circuit elements. This modelling is then applied to more complex AC concepts such as inductive transmission lines and secondary frequency response, to demonstrate the applicability of these elements within decentralised power systems.

This modelling is then extended by examining the proposed power system under certain non-ideal conditions in chapter 5. By incorporating a delay into the response of a decentrally responding node, an instability can be identified and predicted. This is demonstrated by software simulation and verified on a hardware implementation. The instability is influenced by system inertia, showing the system dependence on inertia. In the interests of a decentralised system, an initial autonomous means of determining the required inertia to implement is demonstrated using both software and hardware.

The culmination of this work is then demonstrated in a few possible real-world scenarios in chapter 6. These scenarios are conducted on a power-hardware-in-loop simulator. These verify the ability of the power system to operate with or without energy storage using solar based generation alone. These situations include load fluctuations and the addition/removal of generation resources.

Finally, the conclusions of the research are presented and followed with suggestions for further research and investigation in chapter 7.

Chapter 2

Literature Review

The history of electrical power systems reveals the legacy of thinking and grid control mechanisms that are currently employed. Recent ecological goals has shifted the objectives of the modern power systems. Power systems have had to evolve from supplying dependable electrical power from hydrocarbons to supplying reliable energy from ecologically sustainable but intermittent power sources. This inevitably creates an impasse.

Due to the tight control that could be exerted over few generators, it has been possible to tightly regulate the grid parameters via central control. The operation of a power system has been broken down into various objectives for which there are differing responses which rely on the stringent control of generation. Ecological goals lead to reduced controllable generation and hence worse regulation of power system parameters. The introduction of distributed generation sources as a response to the world prioritisation of clean power sources, such as solar photovoltaic, as residential generation solutions, has led to the so called "gold-rush of grid tied" [6].

This has lead to research into the required techniques to micro-manage local resources and loads, termed microgrids. The objectives of this research are primarily concerned with the adoption of renewable sources within an existing grid framework. While this direction of research does address the environmental and ecological imperatives of the existing global energy sector as a whole, it does little to address the energy requirements of one-fourth of the population of the world population without access to electricity [7]. Around 1.6 billion people are too distant from traditional transmission infrastructure to be connected with conventional power plants [7]. The differing constraints of an islanded system within a rural context is rarely explored.

For example islanded power systems may be too small to make effective use of medium voltage transmission and may their transmission systems tend to be more resistive, than

inductive. This can reduce the effectiveness of certain existing decentralised techniques without the appropriate changes. Furthermore, modern islanded power systems may utilise electronic inverter based generation exclusively, which creates further constraints on the protection coordination and management of these systems.

2.1 History of power systems

In order to investigate the origins of certain techniques used in grid control it is useful to examine the origins of early electric power systems.

In 1878, Thomas Edison started work on the first electric light and formulating the concept of the centralised power station to supply lights. This doubtlessly drove the development of large scale electrical generation to supply power [8].

Some early electric power systems utilised water power. Some steam generation, for example Pearl Street by Thomas Edison in 1882 supplying DC for 10000 lamps. Where roughly at the same time a water wheel is used to supply power in Wisconsin, and in Germany the first transmission line was created. The first AC transmission system was demonstrated in 1886, by William Stanley Jr. [8].

These systems represent some of the earliest attempts to provide generation at a location separate from the consumers. These early systems were isolated plants. One plant, consisting of multiple collocated individual generators, supplying its load alone.

2.1.1 Systematic construction

While early generation stations could supply the power as required by its loads, it was noted that certain stations had different load-time profiles. It was thus beneficial to start bringing together isolated generation stations. In July 1900 a transmission line in Colorado started construction which eventually led to the interconnection of a steam-based hydro plant with two other gravity-hydroelectric plants. This is essentially one of the first examples of an interconnected power system, or electrical grid. Thereafter, the first regional power system was constructed in 1935 [8].

2.1.2 Regulation of frequency

Before the early power systems of Tesla and Edison of the early 1880's, the question existed of how best to regulate the rotation of a spinning machine. Two papers, Siemens [1866] and J.C. Maxwell [1868] attempted to address these issues by exploring different governor

techniques applicable to the operation of a mechanical machine [9, 10]. At the time it was desirable to control the speed of machines with varying loads and minimal deviations in the machine's speed. While Siemens presents an alternative governor that utilises liquid, Maxwell attempts to mathematically define the conditions for stability. It should be noted that the analysis covers operation of these governors under dynamic conditions where the governor itself may be subjected to external forces. Primary to the published analysis was the response of the governor and related system when considering the resistance of the throttle valve control.

The design of these governors are essential to the regulation of the rotary speed of the mechanical devices of the time. It is inevitable that these governors would be used to regulate the rotary velocity and hence electrical frequency for the first examples of generation at the time. These advancements would allow for the tight regulation of rotary velocity, which would set the benchmark for future systems.

While regulation of the power system frequency was essential at the time and is essential for legacy systems which utilise synchronous electromechanical generation it is not entirely required in the modern power system. Most modern devices utilise DC internally or are designed to operate on a wide range frequencies and voltages in order to make these products marketable in multiple global markets.

2.1.3 Present-day usage patterns

During the golden age (1945 - 1965) economic growth and cost reductions led to the construction of coal-steam generation closer to the coal mines. The inclusion of computers also led to improved systems and hence reduced costs. This led to the increased uptake in electrical household energy [11].

This inevitably shaped the way by which electricity has been and still is perceived and used. At the time main elements of generation were highly dependable and low cost. This is important to note when considering the direction energy markets are currently taking in trying to maintain present resilience patterns.

Adoption of intermittent distributed renewable generation is on the rise, due to increased environmental awareness and a reduction of the costs for generation and storage systems. Therefore, requiring an extension of communications and processing infrastructure from the power network transmission level to the distribution level to maintain the existing hierarchical control techniques. Hence the evolving new power system, from early 2000's, contains

bidirectional power flow due to intermittent generation which introduces new challenges for the power network [12].

This led to the development of a microgrid. Microgrid here refers to an collocated set of loads, generation and storage devices that are under local control and can operate grid tied or islanded [13]. This definition reveals the origins of this form of research as being largely related to grid tied situations. While this is a legitimate issue in developed countries, it is less applicable for undeveloped countries and locations. Further the legacy of existing grids is present in the way these systems are controlled. Microgrids tend to rely on a traditional hierarchical control strategies with recent developments tending towards cooperative multi-agent controllers [12].

The objectives of these systems are still predicated around trying to ensure that the consumer load is met at all times. While this goal is necessary to ensure a seamless transition from existing grids to realise sustainability goals, this is economically expensive. This form of thinking is a limitation to the electrification of rural Africa and other undeveloped areas.

2.2 Microgrids

The pace of technology has made electrical power easily available to most through electrical power networks. Additionally, the higher availability of technology has made it possible for private groups to utilise their own generation in addition to power available from the utility power grid. This has led to the study and development of microgrids. Microgrids are defined as electricity distribution systems containing loads and distributed energy resources which can be operated in a controlled, coordinated way either while connected to the main power network or islanded (From Cigre' WG6.22 [13]). Present focuses in microgrid research include tariff optimisation [14, 15], autonomous generation load sharing [16–19], support for islanded conditions and the subsequent resynchronisation to the utility grid [1, 18–32] and the inclusion of aggregate load management to emulate continuous frequency response [20, 33–48].

There are many areas where due to geographic, weather or economic reasons, it is not feasible to obtain a connection to a utility grid. In these areas the technologies and techniques used in microgrids may not be applicable to these remote power networks.

2.2.1 Remote power networks

In the Cigre definition for microgrids WG6.22, there is the mention of islanded operation, as a contingency, a possible condition through which a microgrid must be able to operate through [13]. The definition does not make mention of the time through which the grid must sustain operation when islanded [19–23]. This is largely due to the fact that most microgrid research occurs for populated regions with easily available connection to larger, highly reliable, power grids.

The challenges of an islanded power grid are similar to those experienced in utility power grids. Utility power grids are by their very nature islanded. The smaller scale of the islanded remote power network exacerbates certain issues which are not apparent in large scale power networks (Generation capacity typically larger than 1 MW) [49]. Smaller loads whose operation may be insignificant to larger power networks have a much larger effect in smaller power networks [50].

Typically systems with a total generation capacity of less than 1 kW utilise DC, while systems between 1 kW to about 10 kW will utilise single-phase AC as they will not require the additional benefits of three-phase AC. The power systems of interest are three-phase electric power systems with an installed generation capacity of approximately 10 kW to 100 kW. Therefore typical applications may include agriculture and relatively small scale mining operations. Due to the lower generation capacity of these power systems, they tend to be low voltage (400 V/230 V or similar) and do not require transmission systems of transformers and lengthy high voltage lines.

2.2.2 Renewable Generation Sources

In the interests of sustainability and conservation, renewable energy sources are being used more frequently. Of particular popularity is solar and wind generation sources. Due to their popularity, development of wind and solar generation has reduced their energy cost to less than the total energy produced during its operating life. In addition, these sources, solar in particular, can be deployed anywhere as required. These sources are generally added to a power system after commissioning, hence methods of ensuring autonomous load sharing and synchronisation using the grid frequency have been researched [1, 16, 51]. The power generation of these sources are time varying and may change unexpectedly. In the case of a grid-tied microgrid the required power reserve is available from the connected utility grid.

In an islanded remote power grid case, unless dependable generation is available as frequency response reserve, the islanded grid will be forced into a blackout condition during

periods of reduced renewable generation. In existing systems that utilise renewable energy sources, frequency response reserve generation is provided by the use of diesel generation which is part-loaded, termed hybrid power systems [24, 26, 28, 31, 32, 52]. In the interests of sustainability this is not an optimal solution [46]. The logistics of diesel delivery also present a difficulty especially to users in remote locations [24]. This has led to the development of energy storage systems which can provide power during periods of reduced generation, while absorbing power during periods of excess generation availability. These storage systems can respond quickly enough and are thus frequency response reserve as well as "spinning reserve" [46, 51, 53, 54]. The initial establishment of storage systems is economically costly.

2.2.3 Demand Response

From a power balance perspective, a reduction of the power demand is equivalent to an increase in generation. Rapidly reducing the load requirements on a grid can be used to avoid an overload condition during periods of reduced generation. The concept of using the frequency to allow decentralised loads to respond to the power system frequency was first proposed in 2006 [55]. This allows for a fundamental change in the manner in which power systems are envisioned. Typically, most power systems operate on a technique where distributed generation responds in a decentralised manner to the load demand as a means of primary and secondary response (termed "generation follows load"). The concept of responsive loads, allows for loads to follow generation and thus assist in primary or secondary regulation (termed "load follows generation"). This enables the autonomous control of loads which similarly to autonomous generation control, improves the plug and play capabilities of a power system.

In utility power grids loads have been switched off, or shed, as a means of avoiding overload conditions. During periods during late 2007, 2008, 2014, 2015 and more recently, 2018, South Africa experienced a time of "load-shedding" where despite total generation being less than the total peak load demand, a grid-wide blackout was avoided. This was mainly introduced as a form of tertiary regulation, with very little "load-shedding" being performed as a primary regulation response.

Additional schemes assist by deferring demand. This is the technique of reducing loads during certain periods, with the trade-off of increased power demand later. The net result of this is the same transfer of energy while the demand profile is altered as required [33, 35, 39, 56, 57].

Ripple control has been deployed as a means of deferring demand. Ripple control is generally installed in residential areas, to control loads such as electric water heaters. Ripple control relies on the injection of a high frequency signal onto the power signal to facilitate one way communication from the utility to the receivers in residential properties. Ripple control has several practical issues due to its implementation which reduces its effectiveness to correctly change states, pejoratively impacting its public perception. An issue with ripple control is attenuation resulting in the ripple control signal being too small leading to residential loads staying in an off condition [58].

A more reliable approach is to utilise the power system frequency. This is inherently the largest signal on a power system and should not suffer from attenuation related issues. Since the power system frequency is often strongly tied to the flow of power it is possible to improve the grid stability by responding appropriately to frequency deviations.

Deferring demand is easily achieved with household appliances that perform heating and cooling tasks. These systems can allow the temperatures to deviate from the nominal values, by interrupting or increasing operation, thus reducing or increasing their power demand [35, 39, 48].

Simulations and existing research have shown the implementation of frequency responsive load as a form of demand response to be effective means of improving system frequency response to changes in generation and demand [35, 36, 39, 40, 43, 55, 59–67]. Existing research focuses mainly on loads that are switched on and off. In these studies the large number of binary switching loads were programmed such that the aggregate affect of their contribution to the connected power network is similar to the continuous profile of droop control [39]. As such as the frequency decreased, indicating a deficit of generation, the aggregate affect of the controlled loads was a continuously variable reduction in the resulting power demand [34, 39, 40, 68]. Factors such as time delays due to discrete digital controllers can cause these control schemes to have a pejorative effect on the overall grid frequency regulation [69, 70]. To reduce the delay time of the nodes communication systems are utilised [53, 71]. This removes flexibility inherent to systems based entirely on frequency measurements, adds a potential failure point and may represent a privacy concern to load owners.

In remote power systems aggregation is not possible due to the smaller size of these power systems resulting in fewer total loads [50]. Hence, it is impossible in an islanded remote power system to have the power demand of loads be autonomously varied in a manner that reasonably approximates a continuously variable load. Studies performed on distributed frequency responsive loads to date either implement a standardised droop control

like curve (such as [39, 72]), or rely on a model of the power system to be determined prior to commissioning (such as [73]). Issues with the noise in the frequency measurement (for example [60]) are exacerbated on remote power systems which may have a larger penetration of inverter based generation sources. Furthermore, issues experienced with the delayed response of a responsive load will be amplified by a remote power system with significantly less stabilising inertia compared to utility scale power systems.

2.2.4 Demand Response in Voltage Regulation

In AC power systems, most voltage and frequency control is performed by using the real power/reactive power decoupling assumption. This simplifies the control of voltage and frequency of a power system as being dependent on the reactive and real power respectively. This assumption holds in systems with largely reactive transmission lines [1, 74]. In the remote power systems of interest, the transmission lines connecting generation and load may be relatively short. Shorter transmission lines tend to be more resistive than reactive. As a result voltage regulation is now a function of both the reactive and real power in the transmission line. Therefore, changes in the load demand or generation of a node will result in a change in the voltage at a node. It is possible to regulate the voltage at nodes in a power system by manipulating the power consumed and generated at a node [72]. This has also been demonstrated using distributed demand response [72, 75].

2.3 Electrical Power Grids

The decision to use AC or DC as the transmission medium of the energy was decided primarily based upon the abilities of the technology of the time. In the early days of electrical transmission it was significantly more feasible to use AC. AC could be easily transformed to higher voltages improving the efficiency of energy transmission from geographically separate generation and load. Electromechanical conversion in AC systems was also realised using the induction machine, a cheaper robust machine due to its lack of friction components (brushes/commutator) required for operation [8, 76].

More recent developments in embedded processors and semiconductors has made DC voltage conversion more economically and technologically feasible. This has allowed DC to be reconsidered for use in modern power systems. Many modern consumer devices operate using DC, with very few devices explicitly requiring an AC power supply for its fundamental operation. Hence the future of electric power systems will inevitably be comprised of a

combination of both AC and DC systems. The system type (AC or DC) will be determined by the requirements on a case by case basis. The converters connecting AC systems to the DC systems need to be carefully controlled, preferably with both AC and DC systems displaying similar dynamics, as it allows DC systems to be easily connected to existing AC systems and vice versa.

2.4 Rural Islanded power systems

There is research that is directed towards the electrification of islanded or undeveloped areas. This often takes one of two common forms.

1. Fixed battery and photovoltaic panel DC systems.
2. Diesel generator based systems.

The first item is often sold as a turnkey solution with a set of panels and batteries. Small versions of this can supply some light to medium loads (approximately 10 W-1 kW) with DC. These can be sold as low cost systems with a photovoltaic panel and a few lights. These are economically attractive, as the initial investment is low. Larger size variants of this do exist, but use AC to supply larger loads (1 kW - 100 kW). These systems are limited to their initial design. If more loads are required, these systems cannot be extended. Very often the only way to expand a system is to acquire a second independent system or acquire compatible systems from the original manufacturer.

The second item is directed more towards higher electric load systems (1 kW to 1 MW). These systems are the evolution of the existing diesel generator systems, are often AC and include renewable energy sources. They have the disadvantage of requiring the diesel to be part loaded at all times unless significant storage is available at all times. These systems are therefore heavily reliant on a source of diesel fuel. The relatively low initial costs make these systems a more attractive means of obtaining high resilience generation in remote locations. These systems also include small individual generator units to supply households and businesses in areas where an electrical grid does not exist. An example is the case of Nigeria where due to a lack of adequate infrastructure, diesel or petrol form a primary source of energy [77].

Newer systems do exist whereby the renewable sources and some form of storage can wholly take over the complete load. However, they rely on a central controller to co-ordinate these systems. The processing and communication infrastructure involved adds cost and limits scalability [78].

2.4.1 Changing load states in a remote power system

In a power grid, a device turning on, immediately consumes power from the grid. Initially the power consumed by the device will come from the energy stored in the inertia of a rotating generator (essentially a mechanical storage system) resulting in a change in the grid frequency. Similarly with a load switching off, except the frequency will increase until the generation is decreased. If a load responding in sympathy to changes in the grid loading represents a large proportion of the grid's load, this can result in a cycle of switching that may result in an unstable condition [50].

In power networks, a single device switching will result in a change in the grid frequency. In utility scale grids it requires millions of Watts to cause a 1 mHz change. For example the Eastern Interconnection of the United States of America (EI) has an approximate frequency power response of $25 \text{ MW} \cdot \text{s/mHz}$ [79]. The South African electrical power utility, Eskom, a significantly smaller power system (approximately 38 GW [80] vs EI 400 GW [81]), has a response of approximately $1,4 \text{ MW/mHz}$ [82]. This is largely due to the relative scale of thousands of tons of rotating machines involved in generation at a utility scale. Following a prolonged change in the grid frequency, a power grid will make use of reserve to restore the power system frequency. This time period is typically measured in tens of seconds to minutes.

By means of comparison a remote power system will have a significantly smaller generation and inertial elements. In smaller remote power systems it may take only a Watt to cause a 1 mHz/s change in frequency [16].

2.5 Grid control strategies

When it comes to managing power systems, there are three basic control topologies; centralised, decentralised and distributed. Centralised control relies on a single central node having access to all measurements and determining all setpoints. This poses challenges on the communication and processing of the various values. Decentralised control is the decomposition of a common objective to multiple control elements jointly responsible for deciding actuation. Distributed control is the organization of multiple elements jointly responsible for micromanaging actuation [83].

The choice of grid control strategy depends mainly on requirements of the power system. The basic requirements of any AC power system are

- Frequency control

- Voltage control
- Protection

The basic requirements generally occur relatively quickly (1 ms - 1 s). Therefore, these requirements tend to be met with decentralised techniques. More complex systems such as modern microgrids add further functionality, namely

- Cost optimisation
- Grid synchronisation and islanded operation
- Load and Generation forecasting
- Black starting

These additional functionalities are generally only financially feasible at the higher power levels and hence only used on larger power systems. These features rely on communication between different nodes and significant processing capabilities. Hence, these features add technological complexity and economic cost [84].

The introduction of renewable energy sources in a distributed form results in certain areas having a net power export during periods. This results in local voltage instabilities due to the power flow across distribution transformers. The formation of existing micro-grid research aims to address this issue, among others. Of additional focus is regular operation of the grid-tied system, in the event of an islanding condition, which generally relies heavily on local redundant levels of generation and storage.

The first approach to improving frequency response is termed "centralised control". This utilises a central control agent with knowledge and effective control over a majority of grid elements [83]. This technique relies on advanced reliable communication systems and hence is mainly suitable for utility scale control. This technique is more appropriate for a small number of generators as the communication requirements increase as more generators or controlled nodes are added.

An alternative is a decentralised approach. This technique has various sub-classes of implementation [83]. This approach utilises multiple control elements which are jointly responsible for deciding actuation. This does rely on some form of communication over a significantly smaller area and number of actuators.

The downside of this approach is that frequency regulation can no longer be achieved with the benefit of load sharing between generation [83]. While this downside of decentralised

control may be unacceptable for regions currently with electricity (often with strict electrical grid regulations), it provides an accessible start point for areas without any existing form of electrification.

2.5.1 AC Decentralised systems

There does exist some work into the decentralised operation of AC power systems. This research tends to focus on the control of the storage elements to ensure balanced loading considering both the dynamic state of charge and the power limitations of the interfacing electronics. This is due to the legacy objective of high resilience power systems, and hence the assumption that all load can be met at all times. In a paper Morstyn, Hredzak, and Agelidis [2016] provide an overview of control strategies for microgrids with distributed generation and storage systems. They reviewed 67 control strategies [85]. Out of the 67, 14 utilised decentralised control strategies, of which 5 were AC. Of particular interest is that 36 %, 56 % and 64 % of decentralised, distributed and centralised controller based strategies were AC respectively. This can be attributed to the relative costing of the systems; for larger relatively high power (> 100 kW) systems, expensive central controllers are cost-effective.

The most basic form of load sharing between multiple generation sources is conventional frequency-active power (f-P) droop control. Droop control mimics the stabilising effect of friction in rotating generation [86]. Early studies on the use of decentralised droops as a means of load sharing showed that droop control can be scaled down to low voltage power systems [87]. The decentralised control strategies tend to focus on the response of the storage elements in a system. For example in Guerrero et al. [2004], the State of Charge (SoC) of the storage elements is used to adjust the droop gain of the storage elements. Here a central control system is used to manage overload and over-generation conditions [88]. In Wu et al. [2015] the units are controlled to change their droop co-efficient to indicate the state of charge, however additional logic is incorporated to include the decentralised control of over-generation [89]. This technique involves the operational mode of the participating inverters changing from voltage source inverters to power source inverters as a circular state machine. This work does not lead to the use of the frequency as an inherent visible indicator of the battery and solar generation state for a new observer which does not know the present operating state. While the transition is conducted smoothly it does not take into account the inevitable varied delayed reaction (due to filtering) of other responsive nodes that will interfere with the state transitions. This is a result of verification being conducted primarily in an ideal software environment.

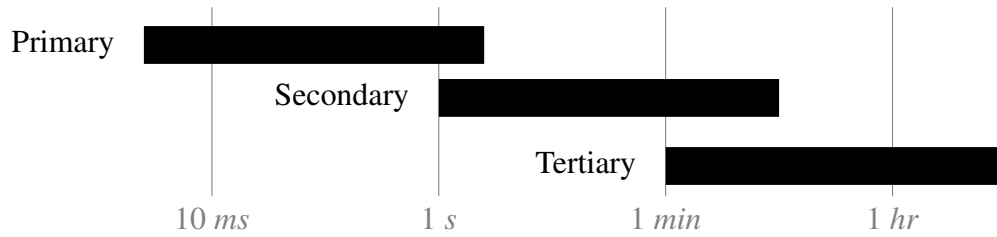


Fig. 2.1 Approximate time scales of generation dispatch.

2.6 Generation Dispatch Nomenclature

The dispatch of generation services can be broken down into the two main components of electric power, active and reactive power. The control of active power is generally more difficult as it calls for the dispatch of energy. Reactive power can be corrected for with minimal active energy with devices such as STATCOMS and hybrid distribution transformers [90, 91].

The dispatch of active power can be broken up into three separate elements, primary, secondary and tertiary response. Their approximate time scales can be demonstrated by Figure 2.1.

2.6.1 Primary response

Primary response is the simplest and fastest response of a power system to a disturbance. This is inherently de-centrally handled by the inertia and droop of generators as only these elements are fast enough to handle faster transients [65]. What should be noted in the research done, the use of droop control is in most cases the addition of relatively low droop percentages on top of constant power setpoints (for example [35, 92, 93]). This is the result of an assumed return to nominal frequency values and nominal power export via secondary response.

2.6.2 Secondary response

Secondary response of a power system is the process of restoring the frequency of a power system following a disturbance. From a basic control point of a view, this requires some form of system memory or integral. This can lead to the unbalanced loading of generation due to differing initial conditions. Hence, balanced secondary response is often achieved

via external communication between nodes, whether from a central controller or distributed decision-making [1, 94].

2.6.3 Tertiary response

Finally tertiary response is the ability of a power system to optimise the use of generation resources. This can be used to optimise the economic costs, ecological impact and/or the reliance of a power system. This generally requires that a controller be aware of the historical generation and load of a power system, in addition to variables that can affect the power system, such as potential cloud cover in the case of photovoltaic.

2.7 AC system DC modelling techniques

Modelling and simulating AC power systems is computationally complex. Parameters such as voltage and current are compounded with elements such as frequency, harmonics and phase shift to name a few. Various alternative grid models exist with varying levels of accuracy. These often utilise assumptions to linearise the model while trading off accuracy. DC power flow linearises AC power flow combining computational simplicity with relatively acceptable accuracy [95–97].

DC power flow modelling linearises AC power flow, with a set of assumptions.

1. Line resistances are significantly smaller than the line reactances. This implies that line losses are negligible and the line can be abstracted to a single reactance.
2. The voltage amplitude for all nodes is equal.
3. Voltage angle differences between nearby nodes is small. This assumption results in the small angle approximation of the sine and cosine terms

This technique linearises the power flows through the inductive elements on a power system resulting in a set of power flows and power angles. This leads to the DC power flow technique being more applicable to the solving of large network power flows with synchronous grid connections.

An alternative analysis technique is the Dommel technique [98]. This technique converts the network differential equations to algebraic equations utilising the trapezoidal rule [99]. This technique models the inductors and capacitors as a series of resistors in parallel with controlled current sources. This technique results in a set of algebraic equations which

combines with nodal analysis techniques provides a method to compute unknown node voltages.

While this technique is useful in evaluating transient conditions such as high frequency component modelling in switch mode converters it does not lend itself to a heuristic analysis of power system design [99].

2.8 Resistive vs Inductive power systems

Preferably power systems are inductive meaning that the transmission is largely dominated by the inductive element. This ratio of series inductance to resistance is described by the X/R ratio. A high X/R ratio allows the voltage and frequency components to be independently affected by the reactive and active power of the elements of a power system. In more inductive systems the inductance ensures a power to frequency relationship since the power transfer over an inductor being a function of the power angle over the inductor [74]. Therefore, droop control in these systems tends to utilise the following relationships.

$$P = f(f_g) \quad (2.1)$$

$$Q = f(V) \quad (2.2)$$

Smaller power systems tend to have much lower X/R ratios which results in active power affecting both the voltage magnitude and the frequency of the system. A typical X/R value for low voltage lines is 0.13 (R/X of 7.7) [87]. This affect is further exacerbated by the lack of inertia present in these power systems. In these more resistive networks, the droop relationships used can be adjusted [100, 101]:

$$Q = f(f_g) \quad (2.3)$$

$$P = f(V) \quad (2.4)$$

These more resistive networks result in a compromise between voltage control and active power sharing. In Vandoorn et al. [2012], P/V droop control is investigated and compared to P/f droop control [100]. Since P/f droop strategy is dependent on a relationship between active power and frequency, present in inductive networks, but not with resistive networks.

This is further exacerbated with the lack of rotary inertia typical of existing electronic generation.

In Bouzid et al. [2015]; it was shown that while voltage is controlled via active power dispatch in resistive power networks, it does not allow for the balanced dispatch of active power [87]. The paper concludes noting that voltage regulation depends on the compensation of the specific line voltage losses, which may need to be tuned for different impedances. This does not lend itself to a scalable plug and play system. The use of virtual impedance, emulating the behaviour of a series connected inductor, in the control loop of the inverter, does allow for the P/f droop controller to operate as if in an inductive power system. This enables the automatic balanced dispatch of active power for linear and non-linear loads [88, 102].

It is noted in Vandoorn et al. [2012], that P/f droop control theoretically results in equal power-sharing between the generators, but higher line losses [100]. The line losses occur due to the Q/V droop causing circulating reactive power between multiple elements in the theoretical resistive lines and purely active loads case. However, large circulating reactive power does not occur in reality [100]. Therefore, conventional P/f control is a valid starting point for decentralised droop response; provided a relationship between active power and frequency can be established. Additional inductance can be added to a power system through the addition of physical (via the filters or chokes) or virtual impedances for the electronic generation units [101, 103].

2.9 Inertia

A recent development in the operation of power systems is the concept of 'zero inertia' power systems [104, 105]. Historically power systems have generated power through the conversion of rotating motion, via synchronous machines. During a transient difference in the power supplied from the prime mover or power source (P_{in}) and the load (P_o), the difference will come from the energy stored in the rotating machine's moment of inertia (J) [74]. This is an example of a decentralised response that has existed in power systems from the origins of the first systems. The inertial response is represented by the classic droop equation

$$P_{in} - P_o = J\dot{\omega} + D\omega \quad (2.5)$$

Where D represents a friction component or a droop response and ω the rotary velocity.

In the general, 'zero-inertia' refers to the fact that there is no rotating machines synchronously connected to the power system [105]. However, the role of inertia may be present through other techniques [106].

In inverter-only power systems, droop is implemented with the inherent linkage of the phase angle between inductively coupled units, determined by the frequency of individual units.

Further, it has been noted that the inherent power-frequency relationship of AC power systems is dependant on either inductively coupled sources or inertia [107]. This is problematic for low-voltage power systems that utilise electronic generation exclusively, as these networks do not inherently have rotating inertia and are likely to be highly resistive. The implementation of an inertial response, whether virtual or mechanical, will ensure the active power-frequency relationship holds, allowing decentralised P/f droop to be used in low-voltage applications.

2.9.1 Limitations of rotating machines

Rotating machines are limited in the energy sources that can be utilised. Rotating electrical generation is easily applied to highly controlled historical energy sources such as diesel, hydroelectric and steam. This requires that the source rotates at a sub-multiple of the power system frequency. Therefore rotating machines do not allow for the easy integration of photovoltaic and wind, the more popular sources of renewable energy. Photovoltaic initially exists as DC electric power and therefore needs some means of conversion from DC to AC.

In the case of wind generation, which exists as a mechanically rotating source, it becomes more complex. It has been established that allowing the wind turbine to vary its rotational speeds in response to the wind speed has results in greater conversion efficiencies, lower mechanical stresses and improved response to transients, compared to fixed speed wind turbines [106, 108]. Popular variable speed wind turbines are doubly-fed induction generator and permanent magnet synchronous machines. These machines are inherently highly dependant on a stable voltage supply to ensure rated electromagnetic conditions. If proper conditions are not met the ability of the machine to extract power from the turbine is affected. This leads to an over-speed of the turbine [109]. This is a source of much of the research into power systems utilising wind generation.

2.10 Electronic generation

In traditional machine based generation, the current carrying conductors are, by electromagnetic design, placed closely to the ferromagnetic materials. This provides the generator with a very large thermal mass, which allows the generator to withstand larger fault currents for long periods of time. Electronic generation does not rely on an electromagnetic interaction. Electronic generation primarily makes use of aluminium heat sinks for fast heat dissipation. Therefore, electronic inverters have a much smaller thermal mass, than their electromagnetic alternatives. Hence, current limiting on electronic inverters is imperative to improve longevity.

2.10.1 Inertia like response in electronic generation

While technically an electronic inverter does not have inertia, the power response of an electronic inverter can mimic the behaviour of inertia. A widely adopted model of electronic inverters models the inverter as a voltage source behind a reactance [110–112]. This is similar to the simplified model of a synchronous machine and hence their behaviour can be analogised [76].

An alternative technique is modelled simply as power injection by the electronic generation. For instance, consider the standard droop control of an inverter [88]:

$$\omega = \omega_0 + G_p(t)(P(t) - P_0) \quad (2.6)$$

Where $P(t)$ is the measured active power of the inverter and P_0, ω_0 is the reference power and frequency of the inverter. The active power regulation is based on the behaviour of $G_p(s)$ may be represented as a Proportional–Integral–Derivative controller (PID controller):

$$G_p(s) = k_p + k_i \frac{1}{s} + k_d s \quad (2.7)$$

If $G_p(s) = 0$ then the inverter will always maintain ω_0 regardless of the loading.

Rearranging Equation 2.6 reveals the similarities to the standard droop equation of a physical machine Equation 2.9.

$$\frac{P(s)}{\Omega(s)} = \frac{1}{k_p + k_i \frac{1}{s} + k_d s} \quad (2.8)$$

$$P(t) = J\omega' + D\omega \Leftrightarrow \frac{P(s)}{\Omega(s)} = Js + D \quad (2.9)$$

Analysing the isolated (with all other parameters set to zero) effects of these components reveals that non-zero values of k_p and k_i (while $k_d = 0$) implements similar dynamics to the droop (D) and inertia (J) respectively on a synchronous machine [113].

Other forms of inertial response have been investigated. This includes operating the electronic inverter by reproducing the electrical and mechanical dynamics of a synchronous machine [114, 115].

This has led to research in improving the dynamic response of an inverter by operating the voltage or Electromotive force (emf) formed internally within the inverter as the back-emf of an actual machine [116–123]. This provides power systems with a source of inertia as well as a faster responding inverter. These forms of control schemes can remove the need for a Phase Locked Loop (PLL) as the control scheme utilises on the flow of actual power from the converter like a feedback loop for a PLL.

Alternatively the inertia like principle is demonstrated when inverters utilise the voltage over the internal DC-link capacitance to vary the power output of the inverter [106, 124–126].

In short the implementation of virtual inertia is a vital component in electronic generation in order to improve the dynamic behaviour of a power system consisting of multiple electronic generation sources [127–129].

When the behaviour of inertia is implemented in an inverter the inverter needs to be capable of sourcing or sinking energy. This often requires a location to store or source the energy. This can come from the rotating inertia of a wind turbine, the DC-link capacitors or other forms of energy storage [106, 127, 128, 130–133]. This needs to be carefully designed such that the operation of virtual inertia does not impede the nominal operation of the generation unit, nor the post fault dynamic operation, which may lead to further reduced generation [132].

2.10.2 Varying virtual inertia

Physically inertia represents a storage of rotating energy. Since the element of inertia is now a parameter inside of the inverter it can be manipulated in order to change the behaviour of the inverter. In Alipour, Miura, and Ise [2015], the virtual inertia on a weakly tied power system was manipulated to prevent pole slip of the generator during a transient [134]. This relied on a return of the system to the nominal frequency (50 Hz for example). In Ackermann et al. [2017], it was suggested that inverters could implement an extremely large inertia during fault conditions in order to improve system stability during and following fault conditions [104]. Constant inertia results in a conservation of energy over time, with the

element neither absorbing or sourcing a net amount, E_{net} , of energy. Provided the frequency (ω) at time T_1 , returns to the frequency at time T_0 .

$$E_{net} = \int_{T_0}^{T_1} J\omega(t)dt = \frac{1}{2}J(\omega(t)^2)_{T_0}^{T_1} = 0 \quad (2.10)$$

Manipulated virtual inertia results in the non-zero net energy over time as now both the inertia J and frequency are functions of time.

$$E_{net} = \int_{T_0}^{T_1} J(t)\omega(t)dt \quad (2.11)$$

2.10.3 Voltage source vs power source converter

A majority of commercially locally available inverters, are either solar grid-tie inverters or backup style inverters designed to supply power independently (from an approximate survey of local renewable resellers). Grid tied inverters means that they synchronise to a power system and generally do not provide voltage or frequency support by default. This is a power source inverter, as it simply supplies a current into the power system to export some active/reactive power. These sorts of inverters are fairly common at higher voltage and power levels as with existing technology it is currently not economically feasible to implement more complex 'hard-switching' techniques required to implement voltage regulation at higher voltage levels [135]. This type of converter cannot form a voltage and hence are not useful in black starting a power system.

The alternative inverter technology is a voltage source inverter. These converters typically use complex modulation techniques to provide some form of voltage. This allows these converters to provide voltage/var support, similar to synchronous generators hence also provide black start capabilities [14, 115, 134, 136].

Inherently a voltage source converter can respond as a power source inverter [89]. However, a power source inverter may not be able to operate as a voltage source inverter.

2.11 The case for hardware-in-loop simulation

The nature of the ideal software environment leads to the development of practically unrealisable solutions. Issues such as noise created by the inverters switching power transistors and delays are often neglected [60, 69, 137–139]. This has led to the development of multiple hardware-in-loop simulators, which allow for the accurate, real-time, largely reproducible and controlled simulation of hardware and grid control strategies [14, 108, 140, 141].

2.12 Conclusion

The development of electrical power systems for the past 130 years has taken advantage of the available energy sources and technologies of the time. Until recently generation has largely been provided by highly dependable and predictable sources of energy. This enabled tight control of grid parameters and hence led to the development of strict grid control regulations. Recent ecological goals are driving the introduction of ecologically sustainable energy sources. These sources are being integrated, while trying to maintain the existing grid regulations. The intermittent nature of these sources, combined with a significantly larger number of these sources, makes existing control schemes difficult to implement while maintaining the same level of service.

The lack of existing infrastructure in underdeveloped regions, means that the regions can afford more relaxed regulations to encourage development. It is therefore possible to utilise decentralised control techniques, which rely on fluctuations of grid parameters. Decentralised control takes advantage of the development of affordable powerful embedded processors available today. The decentralised approach allows these systems to be scalable hence an ideal starting point for low cost ecologically sustainable power systems.

Existing control and modelling techniques are inadequate to assist the development of ad-hoc power systems. A new modelling technique is required to assist with the development of flexible ad-hoc power systems.

Chapter 3

Requirements for Decentrally Controlled Power System.

An electrical power grid has to balance total generation production with total load demand at all times. Since the inception of the first electrical power systems in the 1880's, the focus has always been on the control and dispatch of generation. This is largely because for the most part, the load operates independently of generation.

The developing power system incorporates sporadic unreliable generation sources. This increases the costs, both economic and technical, of being able to provide a reliable source of power. This is where the design of the power system needs to trade-off initial costs for reliability of supply. For scenarios where the primary constraint is financial, security of supply is not a priority. In fact, given poor initial economic conditions followed by anticipated growth, scalability of the power system towards greater reliability at a later stage is a higher priority.

The requirement for plug and play self commissioning of power systems can be met with the use of decentralised control. In this chapter, the minimum requirements to operate a power system with decentrally controlled nodes will be explored. Many of these requirements are heuristic and nominally assumed. Outlying the assumptions can reveal outdated or limiting thinking. This analysis is fundamental to the operation of the power system, and reveals some tradeoffs inherent with decentralised control systems.

3.1 Introduction

A decentralised response approach to power systems may facilitate the implementation of self-commissioning and self healing systems. The application of decentralised control requires

the predefinition of all possible operating regions and the required responses of individual actors in these regions. Its application has become economically and technologically feasible due to advances in embedded processing and power electronics. Decentralised operation of a power system relies on the predefined operation of any dynamic nodes.

In this case creating a decentrally controlled system requires the predefinition of operating regions based on the limitations and objectives of all nodes in the system which tend to be quite similar. These operating regions need to be carefully designed to avoid damaging nodes while meeting grid objectives.

By considering the requirements of the participating nodes of an energy grid, basic operation rules of the power system can be defined. These rules do not explain nor predict the transient behaviour of the system, but should provide a solid framework for the steady state operation of the power system.

3.2 Requirements for Decentralised control

Decentralized dispatch of generation for a power grid requires:

1. There exists an indicator that is influenced by the balance of generation to load.
2. The indicator must be observable by all nodes.
3. Responsive nodes must act upon the indicator to preserve the balance of load to generation.

3.2.1 Regulation of indicator

Power systems expect all parameters to be within a certain pre-established boundary which defines the conditions all connected equipment is expected to withstand indefinitely. Historically in AC systems the voltage magnitude and frequency had to operate within a narrow boundary. This is historically used to avoid electromechanical devices operating near a mechanical resonance or electromagnetic limits. Therefore, these parameters are regulated to return to their nominal values following a disturbance.

In existing AC power systems, localised governors implement frequency regulation (termed secondary response) by increasing their generation output until the frequency returns to the nominal value. This relies on the generation being able to effectively alter its power output, which may not be possible. This inherently requires some form of integral control

response in the governor. It is therefore difficult to ensure balanced loading of all generation elements, as each node will have different initial conditions within the integral.

If the indicator always returns to a nominal position it is difficult to infer the state of the power system from the steady state. This is where the application of perturb-and-observe techniques are used. However, perturb and observe is only truly effective if the perturbation achievable is large enough to create an observable change, which may not be possible as a system scale increases. The number of unknowns in a plug and play system renders any form of model identification significantly more complex and infeasible.

The removal of regulation allows for the regulated element (say frequency) to be used to inform all connected elements about the state of generation and load and therefore contribute to the power system. For instance if all generation linearly scale their output based on the frequency, it will vary from the nominal value indefinitely. Therefore, the frequency becomes an indicator of the loading of all generation. This is predicated on the predefinition of an acceptable frequency operating range that all connected devices will adhere to and operate nominally within.

3.3 Operation Regions

The decentralised control for power systems, relies on an observable indicator on the balance of load and generation, from which decisions can be made regarding the automatic dispatch of generation and load. It is required to ensure the indicator remains within a predefined range of allowable values under all foreseeable conditions. The regions of the highest concern are the under- and over-generation regions. If there are only two types of nodes, responsive nodes and non-responsive nodes, there need to be 3 operating regions to ensure the observed parameter is held within certain bounds. These regions are described in Figure 3.1.

Practically it is not ideal or desired for certain loads and sources to always obey the dynamic rules described by Figure 3.1 at all times. It may be desirable to include operation regions whereby sources and loads obey different rules, applicable to their usage case. For instance, it is ecologically desirable that sustainable forms of generation, such as photovoltaic, provide their maximum power at all times, where possible.

As such the three operation regions is expanded to five regions. These regions describe a hierarchy of dealing with inevitable conditions of any power system that includes nodes that may need to be prioritised over others. These operation regions are shown in Figure 3.2.

More operation regions can be defined as required depending on the breakup of nodes required. The utilisation of 3 node types is sufficient for the foreseeable future power systems.

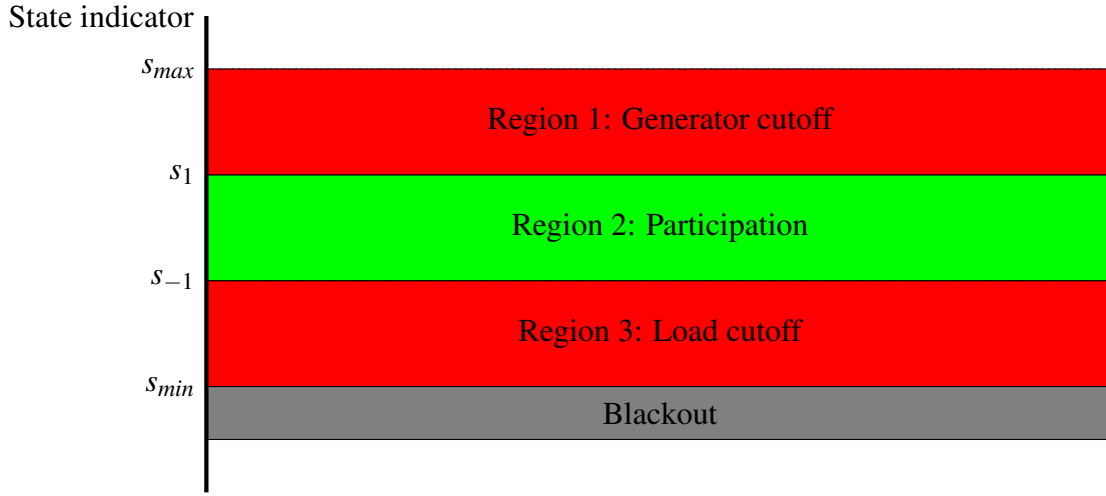


Fig. 3.1 Operation regions for a power system utilising decentralised nodes. Nodes types used include participating and non-participating nodes.

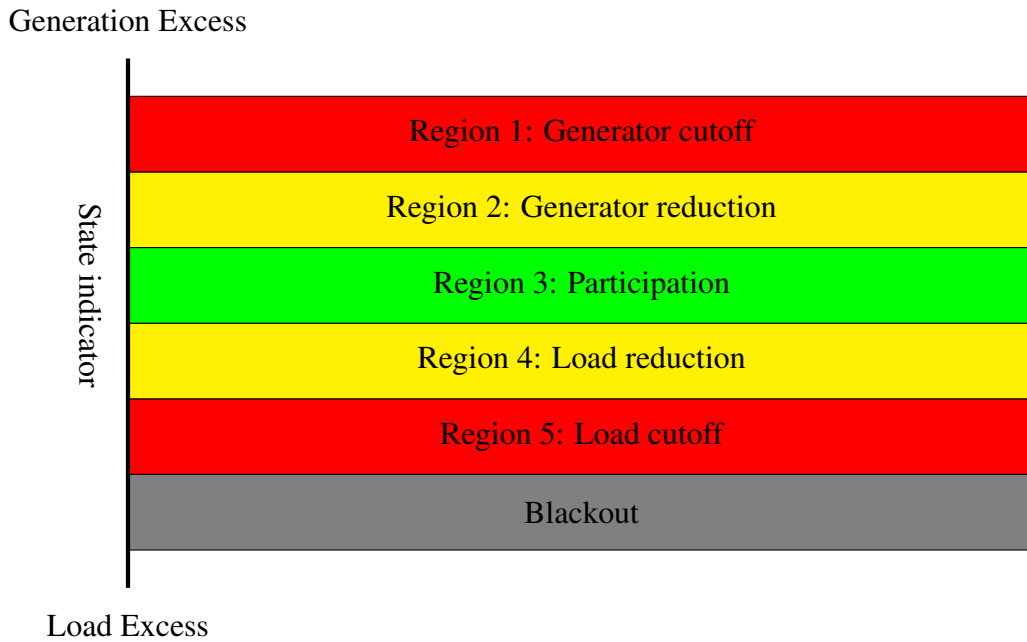


Fig. 3.2 Extended operation regions for a power system utilizing decentralized nodes. Nodes types used include participating, non-participating nodes and priority participating nodes.

3.4 Node types

The establishment of these regions relies on the creation of only three types of loads and generation. These are to be defined as such:

- Continually Responsive nodes

- Priority Responsive nodes
- Non-responding nodes

Actual nodes may not behave like a single element, but as a combination of the three.

3.4.1 Continually Responsive nodes, R

This definition applies to nodes that at all times will be able to completely adjust their interactions with the power system to maintain the generation balance. This primarily applies to storage systems, which at any point in time may change from absorbing power to supplying power. These nodes can change from no power interactions to maximum power interactions at any time.

3.4.2 Priority responsive nodes, P

This definition applies to nodes that should be operating as a constant power source or sink, for as long as possible, but can respond to changes in the state indicator. This provides priority to generation and loads. These elements need to respond to the changes in the state indicator as a last resort.

3.4.3 Non-responding nodes, N

This applies to any form of power supply or load, which does not respond to changes in the state indicator. This can include operating losses of control circuitry for example. These nodes will need to stop operation entirely past a certain operation point. This is required from the power system itself, as it allows for the black starting of the system and may be an operating requirement of the node or device itself.

3.5 Requirements for operation

With the definitions of the response types of node, rules for the setup of the operation of a decentralised power system can be defined.

Firstly we need to define the requirements for the minimum generation of a power system, incorporating responsive nodes and loads. Heuristically, this is achieved if the total available generation is greater than the total non-responsive load.

$$R_g(t) + P_g(t) + N_g(t) > N_L(t) \quad (3.1)$$

Likewise, the total load needs to be greater than the total non-responsive generation.

$$R_L(t) + P_L(t) + N_L(t) > N_g(t) \quad (3.2)$$

This defines the conditions whereby the state indicator can no longer be regulated within the predetermined allowable bands. It also represents the fringe cases whereby the grid will have to shut down and attempt to restart.

This analysis provides a theoretical base for the argument of incorporating more responsive nodes, which aligns with heuristic thinking. Adding responsive or priority nodes increases the total amount of non-responsive load that can be supported by the system. Non-responsive loads represents a majority of existing power system loads which do not respond to changes in the power system frequency. The conditions expressed by Equation 3.2 can be reached in an islanded power system, where there may not be enough load currently available. A solution for this is to add storage that can absorb the power available. However, if the grid has excessive generation, then the storage will be filled and will no longer effectively absorb energy.

Hence, in a practical decentrally controlled power system, it is ideal if all generation is able to adjust its power output as much as possible.

3.5.1 Storage and Demand response

Most loads in modern power systems do not respond at all to the changes in balance between generation and load. As more non-responsive or priority intermittent generation (solar and wind for example) become more prominent in the modern power system, more continually responsive nodes are required.

The increased installation of storage represents a significant investment to the operation of the power system. Alternatively the load can participate by reducing its load based on the indicator. This may be easy to implement via relatively low-cost retrofits, or providing the embedded processor, installed in most modern loads, with a means of observing the indicator and responding to the indicator.

3.6 Operation regions

The objectives of the operation regions is the same; the balance of generation and loading. However in each region certain nodes get priority over others. The operation region in use depends on whether or not the system is operating with excessive loads or generation.

3.6.1 Nominal region (Region 3)

This is where all desirable generation (such as photovoltaic) is operating at maximum power output, while all load is operating at its desired demand. In this region, it is the role of the storage elements to absorb or supply power as required to maintain the energy balance.

3.6.2 Part-load demand (Region 4)

Existing systems make use of a 'load-shedding' procedure, where at certain extreme operation regions, the demands of loads is decreased by various techniques such as 'load-shedding' or ripple control for example. A similar state needs to exist in any power system.

This condition is experienced when too little generation is available to wholly meet the demands of the entire load. During this condition, all available generation and storage elements must be producing as much power as possible, while load is reduced. Therefore, the stability in this region is dependent on loads being able to participate in reducing their demand requirements.

3.6.3 Over-generation (Region 2)

Likewise, with an ad hoc power system design, it is also possible to enter a condition with too much generation. During this condition, the existing generation should decrease its generation output. All loads available draw their full load. Further, if available, loads should draw more power than nominal. For example, hot-water heaters could run a little warmer than their nominal setpoint [66]. Storage elements should be in a charging state, until they are completely full.

3.6.4 Dead/part start (Region 5)

This applies to the starting condition of a power system, as well as to the condition where there is far too much loading on the power system. During this condition, all loads should be

disconnected, and all generation should be supplying as much power as possible. This region serves as a transition between black starting/blackout operation and partial start-up condition.

3.6.5 Generator shutoff (Region 1)

This condition is not expected to be that prevalent, but is a possibility, especially during commissioning and testing. Since all generation should be at minimal or no output power, with all loads at their maximum demand, before reaching this state, it implies too little/no load with too much non-responding generation. At this point the system should be operating such that extreme conditions, such as over-voltage, is not reached.

3.6.6 Blackout

This region describes the operating condition where parameters are below acceptable bounds. The grid system should attempt to restore itself back to acceptable conditions or shutdown to protect grid elements. Nominally caused by the grid voltage or frequency being below acceptable ranges. This region also describes the overloaded conditions, where the total available generation is not sufficient to power the unresponsive loads (such as passive resistive heaters).

The nature of a plug and play power system means that overload conditions are likely. Possible solutions include:

- Modifying loads to co-operate appropriately in this range.
- Using in line systems (such as circuit breakers, relays) or other retrofits to disconnect loads during blackout conditions.
- Grid users manually interact with the power system components by removing offending nodes.

The last item, user interaction, is the lowest cost option, which may have other benefits. By engaging users with their own power systems, awareness regarding the finite nature of energy can be learned. The net result of this is anticipated to be users that are more aware and conscientious of their energy consumption. This will assist with better operation of the power system and may also lead to increased ecological awareness.

The means of operating in this region is outside the scope of this research.

3.7 Conclusion

In this chapter the requirements for the design of a power system is detailed from a high level heuristic agnostic approach. Utilising three node types to define responsive nodes, non-responsive nodes and priority nodes should provide sufficient regions for successful operation of the power system. More node types can be added to extend the range of priorities. In the context of the targeted underdeveloped regions, these regions should be sufficient.

Chapter 4

Decentralised Response DC Power Flow System Modelling

Since all models are wrong the scientist cannot obtain a "correct" one by excessive elaboration. On the contrary following William of Occam he should seek an economical description of natural phenomena. Just as the ability to devise simple but evocative models is the signature of the great scientist so over-elaboration and over-parameterization is often the mark of mediocrity. George E. P. Box, 1981 [142]

Following the definition of the operation regions of the power system, it is convenient to define an analysis technique that can be used to abstract the complex interactions between power elements in an electrical power system. Utilising the conservation of energy as a fundamental basis allows the flow of active power in an AC power system to be modelled as a DC system

This analysis allows for a simplified approach to model the dynamic power interactions in AC systems that can be easily understood with an understanding of basic circuit analysis. This approach provides a framework to determine an easily implementable AC system. This also lowers the knowledge levels required to understand the system hence improving accessibility of the system to those with minimal technical background.

In this chapter the dynamics of connecting various DC sources together is explored. Similarities in the operation between the AC swing equations and DC source models are noted and used as a basis of modelling the AC system dynamics.

4.1 Introduction

Modelling AC systems in their entirety results in a highly complex set of equations, that with the inclusion of high frequency switching devices, is numerically calculated with small steps in time and is extremely computationally intensive.

The ability to simplify the modelling of the system around certain assumptions can provide a lighter computational load, or a heuristic foundation for the design of a power system that can be easily understood by those with basic technical knowledge.

The DC modelling presented here-in models the active flow of power as the equivalent DC current. However, instead of the DC voltage representing the power angle (as is the case in the DC power flow technique) the frequency is utilised as the DC voltage. This technique provides a means of heuristically understanding the active power-frequency relationship of a variable number of active power elements on a power system.

4.2 State Indicators

In order to realise decentralised response, all elements need to respond to a viewable parameter. All elements need to control their loading/generation through observations of this variable. This variable indicates the state of generation of all elements.

Define the generation state indicator variable, s_i , which maps some measured parameter/s to a value between 0 and 1. This represents the monitored variable $x(t)$ between two predefined limits, $s_{u,i}$ and $s_{l,i}$ for an arbitrary system. In order for decentralised control to be implemented in the system, this indicator needs to be accessible to all elements within the collocated system, such that they can all act upon the same observations.

4.2.1 Mapping

If the state indicator is used to map the frequency of an AC system, the generation state indicator needs to be mapped to the maximum allowable frequency deviations during nominal operation. For example, a system has a nominal frequency of $f_0 = 50 \text{ Hz}$ and is allowed to indefinitely differ from the nominal frequency by $\pm 1 \text{ Hz}$. For this case $s_{u,i}$ and $s_{l,i}$ is 51 Hz and 49 Hz respectively, where $f(t)$ is the observed system frequency.

The equation to determine the state indicator is

$$s_i(t) = \frac{f(t) - s_{l,i}}{s_{u,i} - s_{l,i}} \quad (4.1)$$

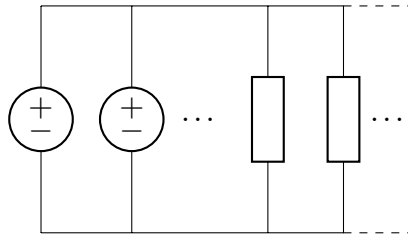


Fig. 4.1 A single area DC grid with an multiple sources and loads.

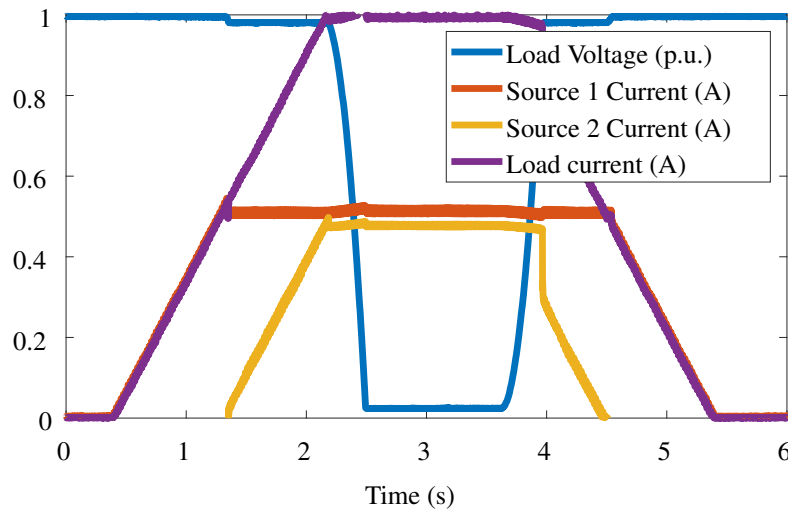


Fig. 4.2 Voltage, Load current, Supply A current and Supply B current, for a ramping current draw of two DC current limited power supplies connected in parrallel. Supply A is set to 10 V (1 *pu*) 0.5 A, supply B is set to 9.8 V (0.98 *pu*) 0.5A.

4.3 Existing DC Grids

While connecting a DC source to one or many DC loads is a trivial exercise in electronics, paralleling multiple DC sources, as shown in Figure 4.1, needs to be carefully considered. Sources cannot simply be connected in parallel, as a slight voltage difference will result in large currents flowing between the sources. As a result practical DC sources include a diode in series with the source. This prevents sources from supplying current to each other. This does not result in equal load sharing between multiple sources.

4.3.1 Parallel DC Power Supplies

This is commonly seen when using a standard DC lab bench power supply which has current limiting. When multiple supplies are connected in parallel the supply with the largest voltage set will supply the load, until it reaches its current limit. At this point the supply will start

decreasing its output voltage, until the voltage reaches the next highest voltage of another source. The grid will then remain at this voltage as the current increases further.

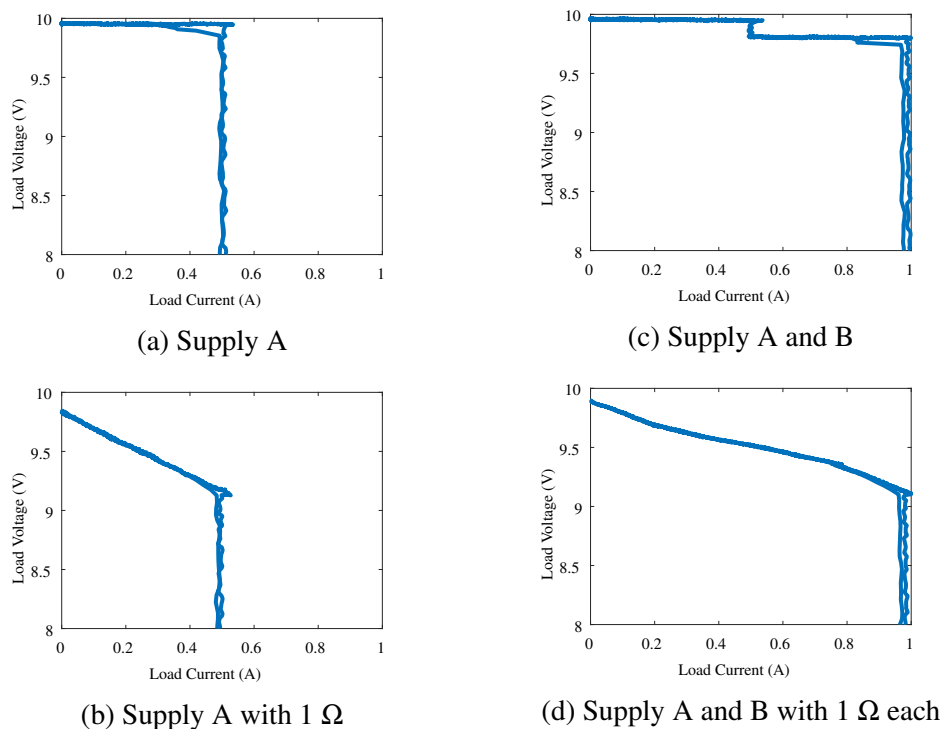


Fig. 4.3 Voltage vs current draw profiles for various configurations of two DC power supplies. Supply A is set to 10 V, 0.5 A, supply B is set to 9.8 V, 0.5 A. (a) shows the load profile of supply A alone without a series resistor, (b) shows the parallel connection of A and B in parallel without a series resistor. (c) and (d) show the response of a single and parallel connection of the power supplies, with a series 1 Ω resistor in series with each supply.

This is demonstrated by connecting two current limited power supplies in parallel to supply a constant current load. The results of a ramping current is shown in Figure 4.2. This yields the load current vs voltage profile shown in Figure 4.3 (c).

While this is an effective means of connecting supplies in parallel and hence increasing the maximum available load current, this solution does not provide any other connected devices a means of inferring how loaded any of the power supplies are. Hence, it is not possible to achieve balanced loading of sources. Therefore, this technique is not suitable for decentrally controlled applications.

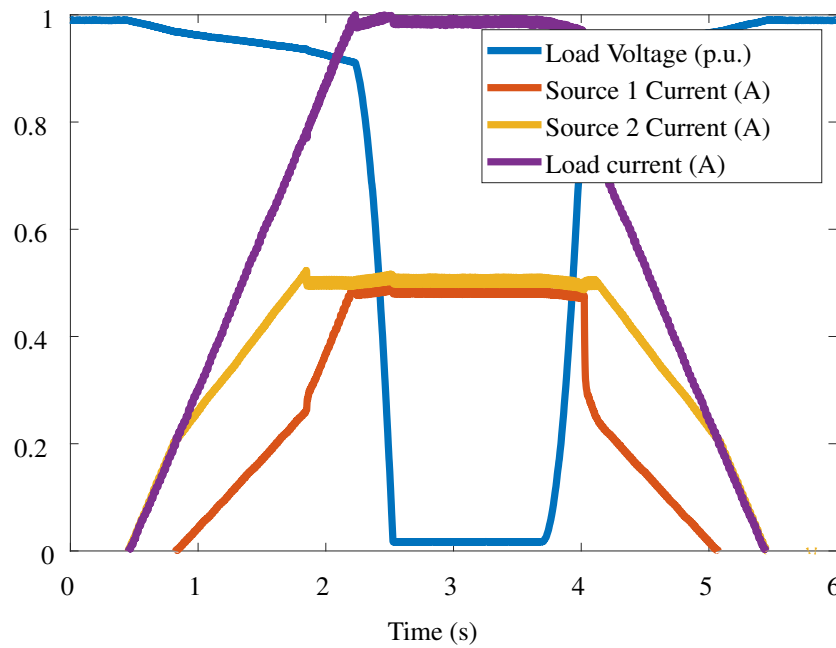


Fig. 4.4 Voltage, Load current, Supply A current and Supply B current, for a ramping current draw of two DC current limited power supplies connected in parallel with a series impedance ($1\ \Omega$) on each supply. Supply A is set to 10 V (1 pu) 0.5 A , supply B is set to 9.8 V (0.98 pu) 0.5 A .

4.3.2 Active Paralleling

In an application note on connecting multiple sources in parallel, Analog Devices provides two solutions [143]. One of the solutions utilises the differential of the load current between the two sources as a means of changing the voltage setpoint of a slave power supply. This is called active paralleling and is synonymous with a centralised controller. In order to ensure balanced loading of all sources, the controller (in this case an operational amplifier) needs to know the current of all devices, in order to control a slave device. This limits the number of sources that can be connected, as the system can only be controlled, as long as the controller can be made aware of all devices.

4.3.3 Passive Paralleling

An alternative solution is to utilise a series impedance with each supply, termed passive paralleling. This achieves balanced load sharing by utilising an appropriate series impedance for each supply, resulting in a degradation in voltage regulation.

The load current vs voltage profile of two or more supplies connected this way (Figure 4.3 (d), Figure 4.4) is the approximate equivalent of a single larger power supply with a series impedance (Figure 4.3 (b)). For passive paralleling, a resistor, R_p , is chosen such that the device, of initial voltage V_{max} supplies maximum current, I_{max} , when the terminal voltage is at its lowest allowable value V_{min} .

$$R_p = \frac{V_{max} - V_{min}}{I_{max}} \quad (4.2)$$

While worse voltage regulation may be undesirable under certain conditions, it is desirable for decentralised control applications. If all elements are connected to the same low impedance bus, as in Figure 4.1 this allows all elements to notice the same deviations in voltage, and hence these systems can respond to these changes in voltage. Since, in the case of passive paralleling, a decrease in voltage is indicative that a source or sources has increased its output current, other elements can respond appropriately.

It should be noted that, due to efficiency concerns, it is desirable for the dynamic behaviour of the resistive element to be provided not by a physical resistive element, but implemented in the control of the power source in question. In modern power sources it is possible to implement virtual impedances via the controlled current response of the source [144].

4.3.4 Inherent load response

In the case of resistive DC loads the load current will decrease with a decrease in the supply voltage. Therefore inherently with DC power systems, there is some form of demand response. This improves overall system stability.

4.4 DC Grid Modelling

Using passive paralleling, the small signal response of the resultant system is modelled by only considering voltage deviations off the nominal voltage. Due to the current limits of a DC supply with passive paralleling the supply will only behave as intended when the voltage is within a specific current range.

Modelling a single supply used in the passive paralleling arrangement is achieved using the Norton equivalent model of the supply, shown in Figure 4.5. The dynamics of the supply can be defined by Equation 4.3.

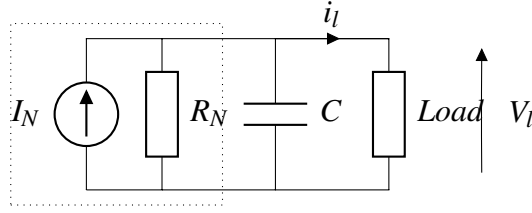


Fig. 4.5 Norton equivalent modelling for a DC source with a series resistor and an external capacitor.

$$I_N - i_l = \frac{1}{R_N} V_l + C \frac{d}{dt} V_l \quad (4.3)$$

Where, I_N and R_N are the Norton equivalent currents and resistances respectively. V_l and i_l are the voltages over and the current absorbed by the load respectively.

Several elements are not covered by this model.

- For voltages higher than the max voltage of the element, a supply will not absorb power, nor will it supply power.
- For currents above the maximum current of the source, the device will no longer supply a larger current.

It is therefore desirable to isolate the region of nominal operation ($V_{max} \rightarrow V_{min}$, $I_{max} \rightarrow I_{min}$) for analysis purposes. Since the voltage from this source is now an indicator of its loading, the voltage in this DC case can be used as the generation state indicator, (Equation 4.1) i.e.

$$s_{DC}(t) = \frac{v_{DC}(t) - V_{min}}{V_{max} - V_{min}} \quad (4.4)$$

As a result the dynamics expressed in Equation 4.3 can be rewritten

$$I_{max} - i_l = \left(\frac{1}{R_N} + C \frac{d}{dt} \right) (s(s_u - s_l) + s_l) \quad (4.5)$$

Noting that in the $\frac{1}{R_N}$ component is only active in the region of interest ($s_u \rightarrow s_l$) and s_l is a constant.

$$I_{max} - i_l = (s)(s_u - s_l) \frac{1}{R_N} + (s_u - s_l) C \frac{d}{dt} (s) \quad (4.6)$$

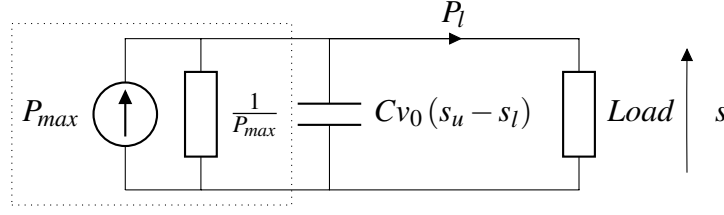


Fig. 4.6 Norton equivalent modelling for a DC source with a series resistor and an external capacitor using generation state indicator.

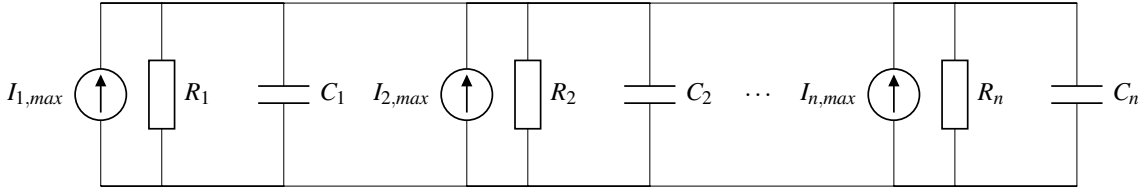


Fig. 4.7 DC modelling of multiple Norton sources connected in parallel via a low-impedance busbar.

Assuming that the voltage region of interest is small enough, then the currents can be multiplied by the nominal voltage ($v_0 = \frac{V_{max} + V_{min}}{2}$) to refer to the system in terms of the active power flows. Provided R_N is chosen to be R_p (Equation 4.2)

$$P_{max} - P_l = sP_{max} + C(s_u - s_l)v_0 \frac{d}{dt}(s) \quad (4.7)$$

Where P_l is the power supplied to the load. Under steady state conditions ($\frac{d}{dt}s = 0$).

$$\frac{d}{dt}s = 0 \rightarrow P_{max} - P_l = sP_{max} \quad (4.8)$$

$$s = 1 - \frac{P_l}{P_{max}} \quad (4.9)$$

Hence under steady state conditions the DC voltage can be used to indicate the state of generation of a single source. Provided that passive paralleling is implemented using the resistor as chosen in Equation 4.2.

Using generation state indicators the Norton model of Figure 4.5 can be redrawn as Figure 4.6.

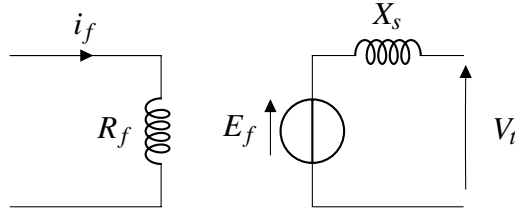


Fig. 4.8 Basic per phase voltage source behind impedance model for a synchronous machine including the exciter winding.

4.4.1 Multiple DC Sources

If N energy sources are used, with maximum power $P_{max,i}$ and capacitance, C_i . The parallel combination of the Norton equivalents (neglecting line impedances), as shown in Figure 4.7, results in the equivalent dynamics

$$\sum_{i=1}^N P_{max,i} - P_l = s \sum_{i=1}^N P_{max,i} + \sum_{i=1}^N C_i (s_u - s_l) v_0 \frac{d}{dt} (s) \quad (4.10)$$

Hence under steady state

$$s = 1 - \frac{P_l}{\sum_{i=1}^N P_{max,i}} \quad (4.11)$$

Therefore with N many DC sources, the voltage can be used as a means of inferring how loaded all generation elements are.

4.5 AC Grid Modelling

AC grid modelling, in particular, 3-phase AC, is typically more complex. The combination of 3 separate voltages, combined with the addition of reactive power, significantly increases the number of variables to be considered in a power system.

Fundamentally 3 phase power systems (hereafter referred to simply as AC power systems) obey the conservation of energy principle. It is from this perspective that this analysis will be performed.

4.5.1 Synchronous generators

The most common generator element of AC power generation is the synchronous machine. This machine, consists of an externally excited rotor, rotating within a 3-phase stator. This

produces an internal emf, E_f , proportional to the excitation and speed of the rotor (Figure 4.8). A widely used form of modelling this machine type is the simple 'emf behind reactance' model [76, 145]. This internal emf (E_f) is modelled in series with the equivalent reactive impedance X_s , with a voltage angle of δ to the terminal voltage (V_t). The produced AC waveform has a frequency, f , proportional to the rotor speed ω . The active (P_{out}) and reactive (Q_{out}) power flow out of the synchronous machine is shown to be

$$P_{out} = \frac{V_t E_f}{X_s} \sin \delta \quad (4.12)$$

$$Q_{out} = \frac{V_t}{X_s} (E_f \cos \delta - V_t) \quad (4.13)$$

The mechanical dynamics are modelled by the swing equation [76]

$$\tau_{mech} - \tau_{elec} = J \frac{d}{dt} \omega(t) + D \omega(t) \quad (4.14)$$

Where τ_{mech} and τ_{elec} represent the resultant torques produced by the prime mover and the electrical power output of the generator respectively. The inertia J of the machine, represents the rotary inertia of the spinning mass of the generator. The droop element D represents the droop elements within the generator. This droop is essential to the operation of the generator, as it dampens the response of the generator.

4.5.2 Governors and frequency regulation

It should first be established, whether the frequency can be allowed to deviate indefinitely from the nominal value. Few modern electronic devices require an accurate power supply frequency. Many devices utilise an internal AC to DC converter to meet their power requirements and are specified for both 50 Hz and 60 Hz AC power. Should a device require an accurate clock, quartz crystals are commonly used.

Electromagnetic devices may require more stringent frequency regulation to avoid saturation issues. Electromechanical devices, in specific AC synchronous and asynchronous machines, may require stringent frequency regulation to prevent mechanical stalling, avoid electromagnetic saturation or avoid certain mechanical resonances inherent in the final application. In those special cases, inverter technology can be utilised to provide frequency regulation and improve efficiency.

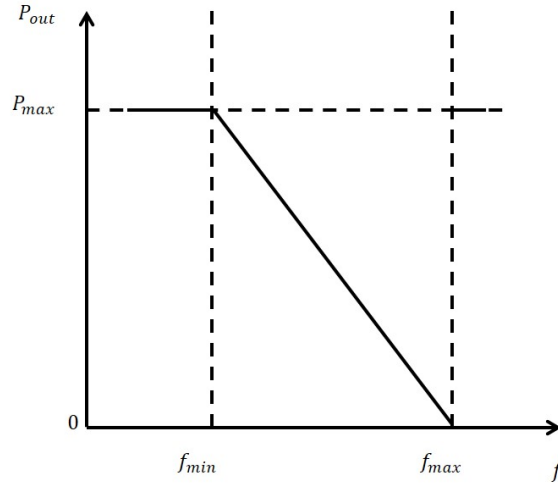


Fig. 4.9 Power supplied vs frequency for an AC connected generator with 100 % droop participation

4.6 Power Flow Modelling for the AC system

A comparison of the resulting small signal models for both AC and DC (Equation 4.14 and Equation 4.3 respectively), reveals the same dynamic elements in the two systems.

4.6.1 AC Systems with Generation State indicator

Firstly it is needed to convert the swing equation (Equation 4.14) into the relative mapping with the generation state indicator. For an AC system define nominal operation to be between the bounds $f_{max} \rightarrow f_{min}$ (using rotary velocity $\omega_{max} \rightarrow \omega_{min}$). Therefore, the frequency can be mapped to the generation state indicator

$$s_{AC} = \frac{f(t) - f_{min}}{f_{max} - f_{min}} = \frac{\omega(t) - \omega_{min}}{\omega_{max} - \omega_{min}} \quad (4.15)$$

Therefore, the swing equation (Equation 4.14) becomes

$$\tau_{mech} - \tau_{elec} = J(\omega_{max} - \omega_{min}) \frac{d}{dt} s(t) + D(\omega_{max} - \omega_{min}) s(t) \quad (4.16)$$

Provided the droop element is controlled to operate only in the nominal frequency range, and to operate from 0 W to P_{max} as illustrated in Figure 4.9.

$$\tau_{mech} - \tau_{elec} = J(\omega_{max} - \omega_{min}) \frac{d}{dt} s(t) + \frac{1}{P_{max}} s(t) \quad (4.17)$$

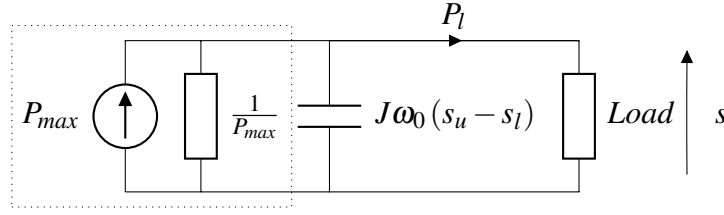


Fig. 4.10 AC Power-Frequency dynamics shown with their dynamic equivalents.

Since Equation 4.17 and Equation 4.7 are dynamically the same, the AC dynamic equivalents can be modelled as shown in Figure 4.10, similar to the DC circuit of Figure 4.6.

From a dynamics point of view this means that the resistance of a DC source or load provides the same dynamic properties as AC droop, D . Likewise for the capacitance of a DC system, C , and the inertia, J of an AC system. This is consistent with the law of conservation of energy. This similarity has been noted previously, in the implementation of virtual inertia strategies for inverters [146]. This similarity has not been extended to the modelling of the dynamics of a system.

Therefore, as proven for the DC systems (Equation 4.11), the frequency is an indicator of the state of generation loading. Practically the AC system frequency is more likely to be consistent over a collocated AC system, as opposed to the DC voltage, where line impedances will affect the DC voltage.

4.6.2 The modelling of transmission lines

Transmission lines can be modelled in their simplest form by a series inductor and resistor with a parallel capacitance. Depending on the application the model may be further reduced. For the case of the DC system, the main element of consideration is the resistive element, R . For AC systems the inductance, X_l , is the main element of consideration. This limits the power that can flow through the transmission line. Analysis performed on AC systems, generally models transmission lines and transformers largely as inductive elements.

The transfer of power over an inductive element is defined by the voltages, V_1, V_2 , on either end of the inductive element X and the power angle, δ , over the element.

$$P = \frac{V_1 V_2}{X} \sin \delta \quad (4.18)$$

The power angle is defined as the difference in phase angle, $\delta = \theta_i - \theta_j$, on either side of the inductor. The frequency on either side is defined as the derivative of the phase angle, $f_i = \frac{d}{dt} \theta_i$. Recall the small angle approximation (section 2.7), $\sin \delta \approx \delta$ and the assumption

that voltage magnitudes are the same at both nodes (V_{nom}). Since the state indicator is defined as $f_i = s_i(s_u - s_l) + s_l$, the equation for the power transfer over an inductive element can be rewritten;

$$P_{i,j} = \frac{V_{nom}^2}{X} \sin \int ([s_i - s_j] [s_u - s_l]) dt \approx k_{L,AC} \int (s_i - s_j) dt \quad (4.19)$$

Where

$$k_{L,AC} = \frac{V_i V_j}{X} [s_u - s_l] \quad (4.20)$$

Compare this to the behaviour of an inductor, $V_l = L \frac{d}{dt} I$, likewise described by the DC state indicators (Equation 4.4).

$$P_{i,j} = v_0 I_L = \frac{v_0}{L} \left[\int (V_i - V_j) dt \right] = k_{L,DC} \int (s_i - s_j) dt \quad (4.21)$$

Where

$$k_{L,DC} = \frac{v_0}{L} [s_u - s_l] \quad (4.22)$$

Therefore the inductive transmission line in AC circuits can be modelled as a DC inductor in the power flow modelling presented. This demonstrates how the modelling can be used to model sub-harmonic oscillations between the inertia of synchronous machines and the transmission lines as a similar phenomenon to the oscillations that occur between an inductor and a capacitor following a disturbance.

4.6.3 Arbitrary System Interconnections

If the dynamics of AC and DC systems are the same and modelled as such, then the desired dynamics of a connection between the systems can be established. This also allows for the interconnection of either systems to each other.

Provided that both systems utilise the indicator for their decentralised control, the interconnecting device can allow for power flow between two arbitrary systems. For example, consider two systems with state indicators s_1, s_2 , interconnected with an appropriate bidirectional interconnecting device (AC-DC converter) with a power limit of P_{lim} . The inter-flow of power between the two systems can obey the following simple function.

$$P_{1-2} = P_{lim} (s_1 - s_2) \quad (4.23)$$

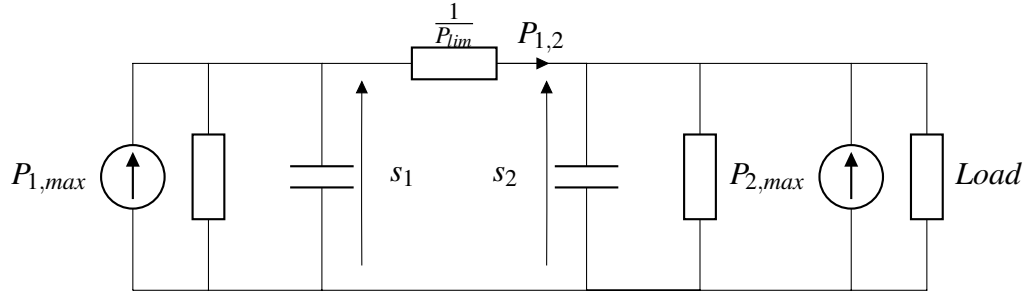


Fig. 4.11 Modelling of the connection between two arbitrary systems modelled using the generation state indicators.

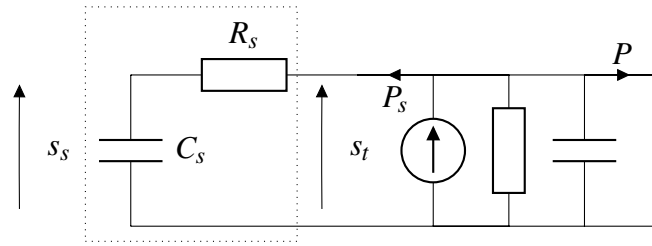


Fig. 4.12 Power flow model of energy storage (C_s) with some interfacing electronics (R_s) to another generation unit.

This way if system 1, has more power available, indicated by a higher generation state indicator, it will transfer power to system 2 and vice versa. Further this linear relationship behaves dynamically as a DC Resistor, modelled as shown in Figure 4.11.

4.6.4 Storage Elements

While the state indicator is used to represent the relative loading on power system elements in the system, they can be extended to storage systems.

Consider a storage element can map its internal storage energy to an indicator between 0 and 1. This is similar to a state of charge indicator that goes from 0 to 1. Ideally the storage element is not directly connected to the power system. Consider that the storage element will interface with a power system, via some form of energy converter (inverter for example).

Therefore the storage element can be modelled as a large capacitor behind some impedance as in Figure 4.12. This produces the power (P_s) versus terminal state indicator (s_s) profile of Figure 4.13.

- As the state of charge increases the storage element will absorb less power but will be more willing to provide power. Thus multiple storage devices will provide power

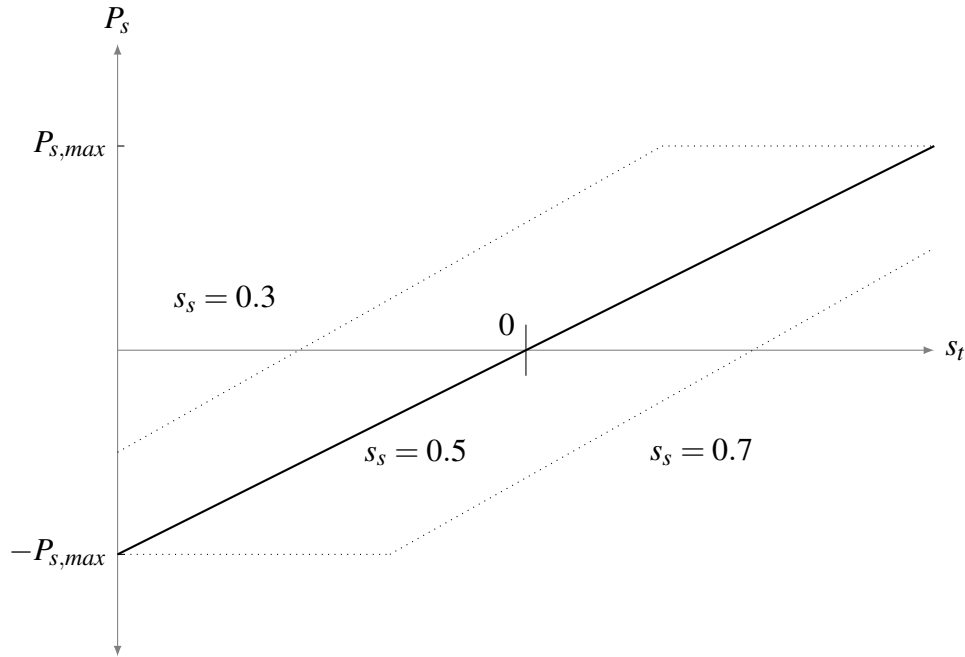


Fig. 4.13 Power flow model of energy storage for various storage levels incorporating power limits

relative to their own state of charge and hence inherently be relatively equally loaded and charged in steady state.

- The more power being absorbed or supplied to the system will result in a larger deviation to the state indicator of the connected system. Elements on the system will notice this and can respond accordingly.
- The flow of power will not be optimised. The charging of the storage element will now mimic the charging of an RC circuit. Therefore, at a point the power supply will have to reduce its power output. Even though theoretically both elements could operate at a higher power level (hence charge the storage quicker).

Therefore, even though this storage system can be utilised in an ad hoc fashion, the inherent tradeoff is a loss of optimisation. It is inherent that the storage will not charge fully, even though theoretically the energy is available. Likewise, the inverse is true. It may be possible to still provide power for a power system, as the energy is available in the battery, but the loading may be too large for the state of charge of the battery with the equivalent resistive element of the interface electronics behaviour.

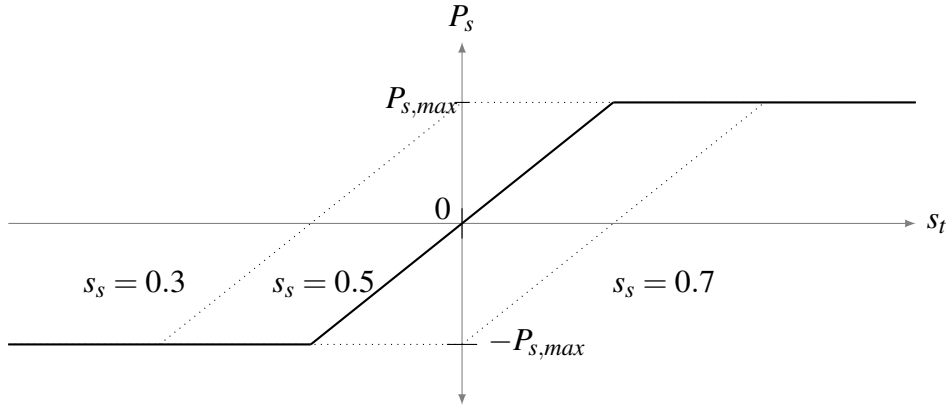


Fig. 4.14 Power flow model of energy storage to allow for higher utilisation of storage system for various storage levels

It is possible to decrease the storage response gain (R_s), thereby decreasing the difference in generation state indicators required to meet maximum power transfer allowed by the storage interface electronics. This will result in the power flow as follows (Figure 4.14).

$$P_s = \begin{cases} P_{s,max} & P_{s,max} < \frac{s_1 - s_2}{R_s} \\ -P_{s,max} & -P_{s,max} > \frac{s_1 - s_2}{R_s} \\ \frac{s_1 - s_2}{R_s} & elsewhere \end{cases}$$

4.6.5 The Effect of Secondary Response

Secondary response is the ability of the system to move from a frequency offset, back towards its nominal value. While droop control alone leads to frequency offsets, secondary response modulates generation output following a disturbance to restore the frequency to its nominal value.

In the power modelling used so far the functionality of secondary response is incorporated by including additional components into the source model. This aligns with the secondary response power being added to primary response.

Take the generic secondary response algorithm, an integral function producing the additional power setpoint P' [86, 147]

$$P' = k_2 \int [f(t) - f_{nom}] dt \quad (4.24)$$

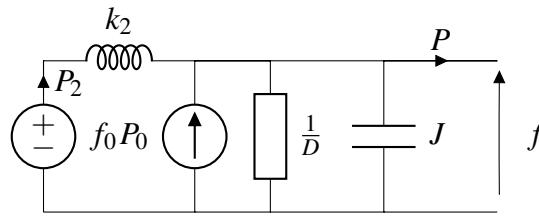


Fig. 4.15 Power flow model of inverter with primary response droop (D) and inertia (J), with the addition of a secondary response loop.

This can be demonstrated to be similar to the DC inductor in the dynamic power flow analysis. This adds an equivalent voltage source to the power flow model as shown in Figure 4.15.

This provides some indicators for why secondary response cannot be used in a decentralised plug and play system.

1. A slight offset in the f_0 or the measurement thereof between different units could lead to circulating active power.
2. An unknown number of nodes with some inertia J and secondary response k_2 can result in a resonance being excited. Using superposition analysis, all inductive and capacitive elements are therefore in parallel and hence create a resonance circuit.

Therefore in a plug and play, decentralised system, secondary response cannot be implemented.

4.7 Dynamic Response

In the operation of a power system, there are four responses to a disturbance in the power balance.

1. Continually increases
2. Continually diminishes
3. Oscillates with increasing amplitude
4. Oscillates with decreasing amplitude

These effects may be measured in either the frequency or the voltage. Since changes in the balance of power result in changes to the frequency, this section will focus on the power and frequency interactions.

Disturbances that result in a continually diminishing or oscillation with decreasing amplitude are preferred to the alternatives. In the grid system as defined, oscillations with an increasing amplitude occur due to discrete controller action, and will be dealt with the next chapter. The continually increases condition occurs with one of two conditions. Either there is too much or too little generation compared with the load. Ideally in a power system, with all sources obeying the dynamics as modelled and all loads obeying usual resistor dynamics, and hence providing load response, this system cannot result in a continually increasing deviation.

4.7.1 Priority

There exists the interaction of priorities when storage and renewable energy sources are introduced to a power system. Ideally, the renewable energy source should be supplying maximum power at all times. The storage system, therefore has the requirement of adjusting its charging/discharging, to maintain the balance of generation to load.

A requirement of the decentralised system is that the system can operate with the stochastic renewable sources alone or prioritise the use of renewable generation. In order to prioritise certain nodes over others, while ensuring the system can operate with a single node, offsets can be introduced.

For example, if a renewable source is set up such that its droop element (D) goes from the maximum available to zero generation on a frequency range of 51 Hz to 53 Hz. Consider then a second generation system that operates with a droop going from maximum available generation to zero generation, on a frequency range of 49 Hz to 51 Hz. Both sources can supply a load if operated independently. This produces the profiles, shown in Figures 4.16 and 4.17. This is considered in section 3.3. Together the system can operate such that if the renewable source is completely loaded, the second generation source can supply the additional power required by the load.

4.7.2 RC Networks

For the power system as defined it is ideal to operate with dynamics that can be modelled as resistors or capacitors alone. This is because the inherent response of a network of an unknown number of resistors and capacitors can always be reduced to single order dynamics

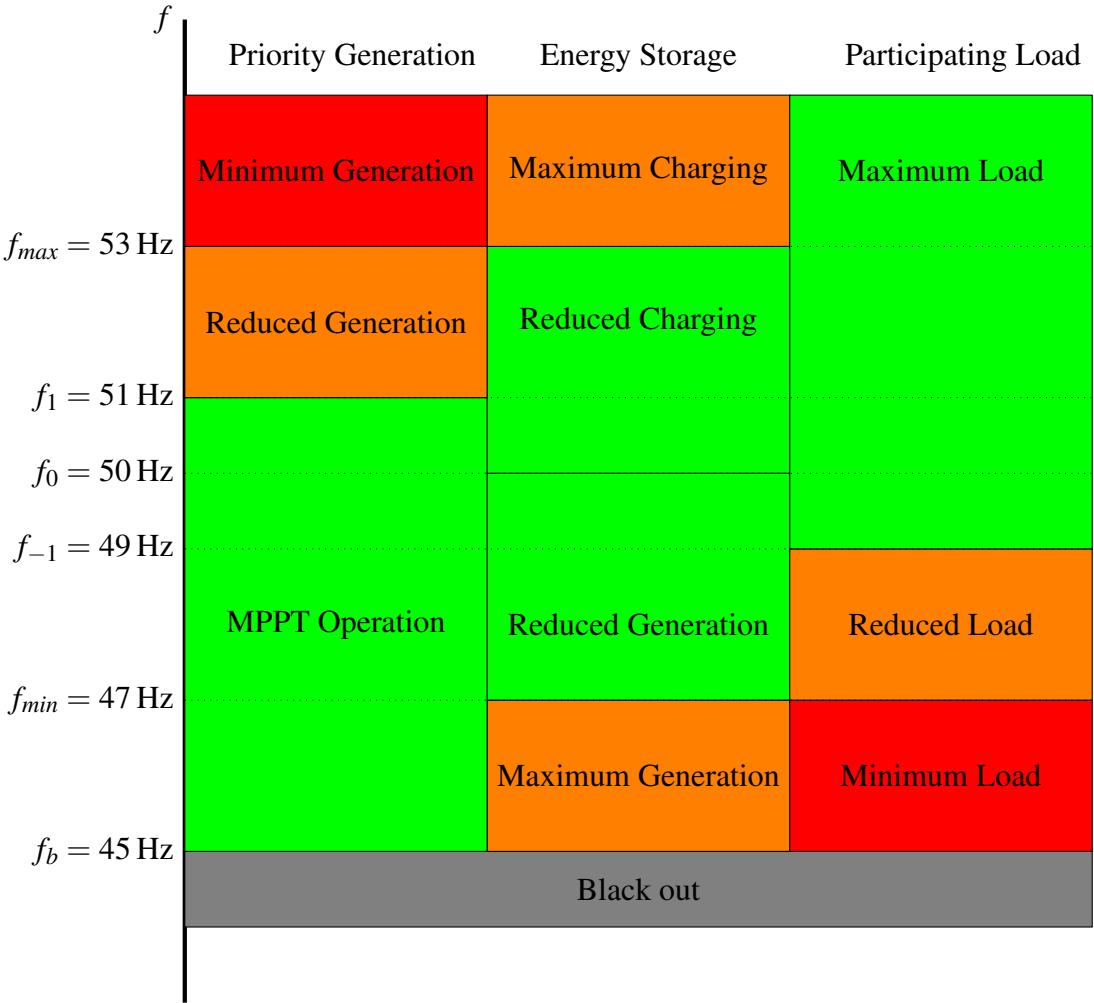


Fig. 4.16 Example operation profile of priority generation with energy storage and participating load.

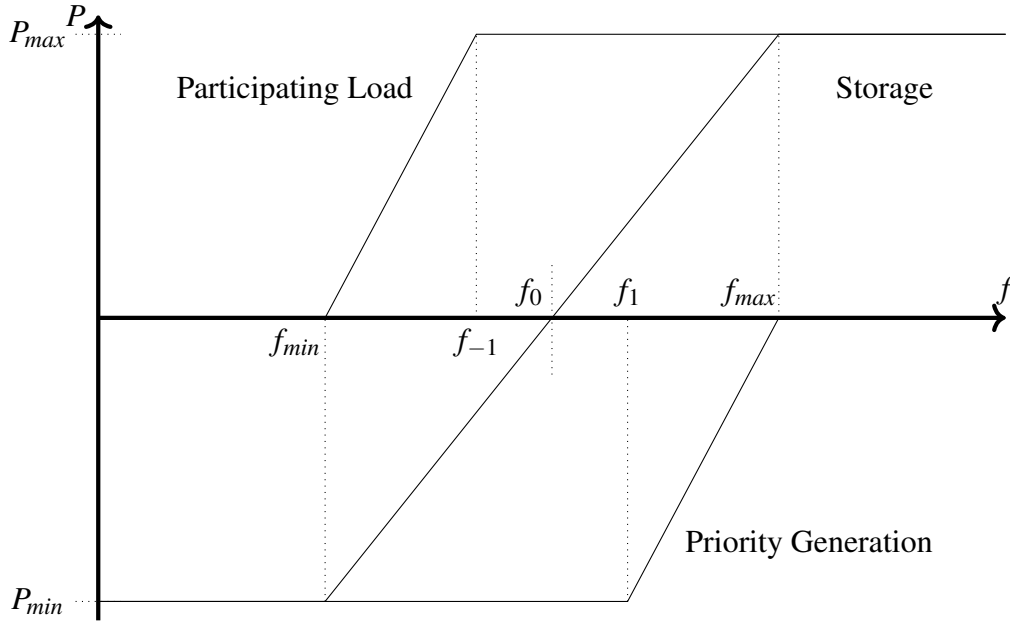


Fig. 4.17 Operation profile of priority generation, energy storage and participating load.

which are unable to oscillate with increasing magnitude [148]. Therefore, it is not likely for a system with decentralised operations such as droop and inertia, with no inductive transmission lines or secondary response to oscillate with increasing magnitude. Hence in the design of a scalable power systems components should emulate the modelled resistive and capacitive behaviours. Elements such as inductive transmission components and secondary responses should be avoided.

This means that the dynamic failures of the system frequency to breach the predetermined limits is theoretically limited to over or under generation conditions.

4.8 Conclusion

Similarities exist between the dynamics of current in a DC circuit and the flow of power in an AC power system. These similarities allow for the abstraction of power flow dynamics in an AC system. Therefore, it is possible to define the desired behaviour of nodes to be utilised on a plug and play power system. Furthermore, it enables AC and DC to be interconnected as desired with the decision of power distribution technology more dependent on the power system load requirements.

Since networks of resistors and capacitors can never be unstable, it is desirable to design power system components to behave like resistive and capacitive elements using the

modelling provided. This analysis provides a framework for the interconnection of AC and DC power systems on an ad hoc basis. Where providing all systems obey the same rules and operate ideally, they can be freely connected and disconnected from each other without leading to significant stability issues.

Chapter 5

Small Signal Dynamics under non-ideal conditions

The modelling and analysis conducted so far considers the ideal behaviour of the power system, with ideally responding nodes. Initial simulations of the developed models indicated that non-ideal node behaviour needed to be accounted for. Of significant interest is the delay in measuring and responding to a change in the frequency.

5.1 Introduction

Undesired reactions to disturbances are typically either an increasing deviation of some parameter or an oscillation with increasing magnitude. Theoretically the means of preventing an increasing deviation has been described in chapter 3. Practically it is possible for operation as described in chapter 3 and chapter 4 to lead to oscillations with increasing magnitude. It is therefore desirable to model the conditions that lead to this undesired behaviour.

This chapter explores the small signal dynamics of a single area power system containing generation, load and inertia connected via a single low-impedance busbar.

5.2 Modelling

The modelling consists of a single low impedance busbar, an inertial component, generation and load. This isolates the behaviour of each individual component to the frequency response.

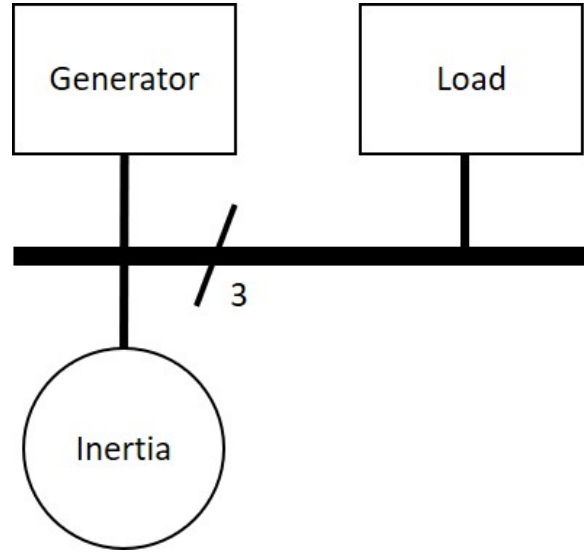


Fig. 5.1 Single area power system consisting of generation and load with inertia connected via low impedance busbar.

5.2.1 Purely Linear elements

Consider the single area power system shown in Figure 5.1, with the generator and load both participating with droop control. The nominal power of the generation and load is given by P_g and P_L respectively, with their droop coefficients D_g and D_l with units of W/Hz. Connected to the busbar is an ideal inertial element, with moment of inertia J , units of $\text{W} \cdot \text{s}/\text{Hz}$, calculated by

$$J = \frac{H \omega_0}{k_f} \quad (5.1)$$

Where ω_0 is the nominal rotary velocity (in rad/s) of the synchronous machine and k_f is conversion from the rotary velocity (ω) to electrical frequency (Hz) of the synchronous machine. The value H is the physical moment of inertia in $\text{kg} \cdot \text{m}^2$. This assumes that the electrical power to mechanical torque conversion is related by a constant rotary speed ω_0 and that the frequency deviations will be relatively small compared to the nominal frequency.

The dynamics of this system can be modelled equally using the block diagram shown in Figure 5.2. It should be noted in this case that $F(s)$ is a function relating the difference in frequency from the nominal value f_0 .

$$f(t) - f_0 \xleftrightarrow{\mathcal{L}} F(s) \quad (5.2)$$

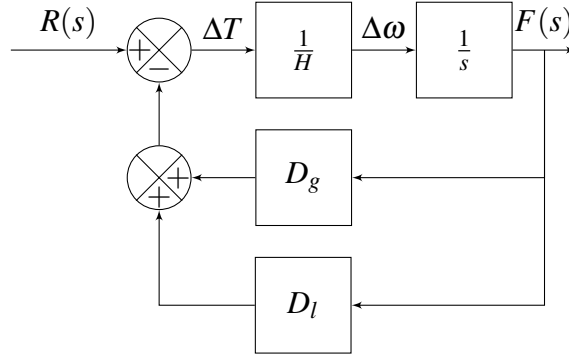


Fig. 5.2 Responsive modelling with responsive loads and generation in the Laplace domain.

This diagram can be reduced to a simple characteristic equation as presented in Equation 5.3.

$$\frac{F(s)}{R(s)} = \frac{1}{Js + (D_l + D_g)} \quad (5.3)$$

The system will remain Bounded Input Bounded Output (BIBO) stable provided the pole of the equation is negative. Thus this system is stable if $\frac{D_g + D_l}{J} > 0$. Since J should be always positive in real systems, stability depends on $D_g + D_l > 0$. Heuristically this implies that provided as the frequency increases, the power consumed by loads should increase and the power produced by the generation decreases (conventional droop [149]). This aligns with the existing models that assume the implementation of droop control on grid connected inverters should improve grid stability [149].

However, this is an idealised system where any responsive element responds instantly and linearly. In the case of the synchronous element the change in speed will be instantaneous. In the case of grid-synchronizing inverters, the internal control system should respond quick enough to respond. Lower cost systems may utilise low-cost devices, which may utilise additional filters that delay the rate at which the device can measure the frequency and hence respond.

5.2.2 Linear Delay

When using a PLL, digital or otherwise, there will be some delay between a change in the grid frequency and the measured frequency. This is inherent in the PLL due to the filter required to transform the phase error, measured on a noisy signal, to a constant input to the voltage controlled oscillator.

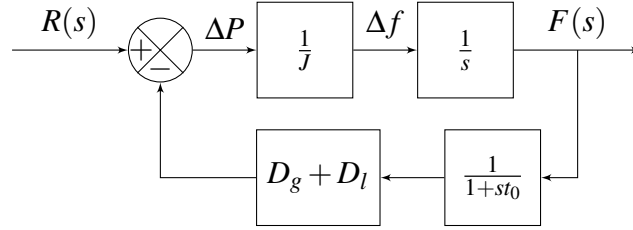


Fig. 5.3 Responsive modelling with responsive loads and generation in the Laplace domain, using a delay to model the controller.

The Laplace transform for a delay or time-shift of t_0 is $f(t - t_0) \leftrightarrow e^{-t_0 s} F(s)$ [150]. This can be approximated to n^{th} orders by Taylor Expansion Equation 5.4.

$$e^{-st_0} \approx \frac{1}{\left(1 + \sum_{k=1}^n \frac{(st_0)^k}{k!}\right)} \quad (5.4)$$

For the sake of simplicity it will be assumed that any delays can be approximated as a single order delay which also represents the transform function of a unity gain, single order, low pass filter. Thus, the analysis is approximately comparable for the approximation of a linear delay or a low pass filter. The system is expanded to that shown in Figure 5.3. It will be assumed that both the generation and load have the same delay time. The system then reduces to the second order characteristic equation of Equation 5.5.

$$\frac{F(s)}{R(s)} = \frac{1 + st_0}{t_0 J s^2 + J s + (D_l + D_g)} \quad (5.5)$$

Using the quadratic equation to infer the poles of the characteristic equation yields the following poles

$$s_1, s_2 = \frac{-1 \pm \sqrt{1 - 4t_0 \frac{1}{J} (D_l + D_g)}}{2t_0} \quad (5.6)$$

Noted that all constants are positive, non-zero values thus the poles will always be negative, therefore this system will always be stable. The damping co-efficient, ζ , is described:

$$\zeta = \frac{J}{2} \sqrt{\frac{t_0 J}{D}} \quad (5.7)$$

Following reductions in inertia, J , or increases in the delay or filter co-efficient, t_0 , the dampening co-efficient decreases. This means that the excursion of the frequency, following a disturbance increases.

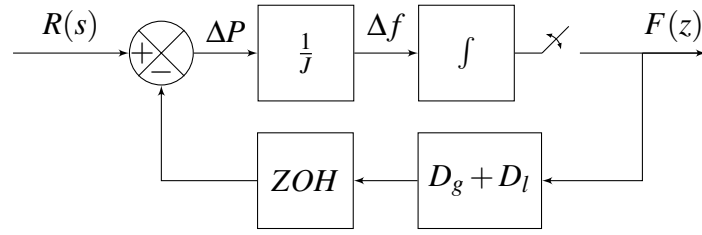


Fig. 5.4 Responsive dynamic modelling in the Z-domain

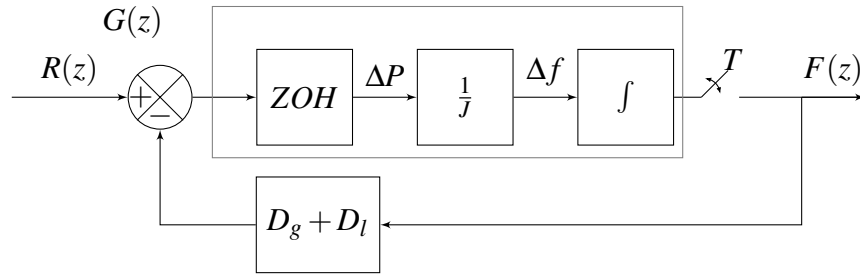


Fig. 5.5 Responsive dynamic modelling in the Z-domain simplified

It should be reiterated that this result incorporates a single delay in the response of the droop controllers. This is useful for the implementation of PLL based inverters, or PLL based load droop controllers.

5.2.3 Discrete Delay

Another means of modelling the response of the generators is to assume that the system is controlled by a digital controller which discretely samples the frequency every T seconds and then makes a decision. This is modelled as a sample and hold circuit implementing the droop response of the inverter.

It will be assumed that all inputs/outputs of the system will be synchronized at the same sampling rate. It is also assumed that the disturbances $R(s)$ are also synchronized with the sampling rate of the control system. By this means, the system model can be simplified to the block diagram shown in Figure 5.5.

Using tables, the Z-domain representation of $G(z)$ is

$$G(z) = (1 - z^{-1}) \left(\frac{1}{J} \frac{Tz}{(z - 1)^2} \right) \quad (5.8)$$

Thus the dynamic equation of the system is

$$\frac{F(z)}{R(z)} = \frac{\frac{T}{J}}{z - 1 + (D_l + D_g) \left(\frac{T}{J}\right)} \quad (5.9)$$

With a pole of

$$z = 1 - (D_l + D_g) \frac{T}{J} \quad (5.10)$$

For BIBO stability in a z -domain, the magnitude of the poles must exist in the unit circle of the z -plane. All the parameters in the transfer function (Equation 5.9) are real. For stability the values of the single pole must remain within ± 1 . The stability criteria of the system is;

$$2 > (D_l + D_g) \left(\frac{T}{J}\right) > 0 \quad (5.11)$$

$$\frac{2}{T} > \frac{D_l + D_g}{J} > 0 \quad (5.12)$$

In the context of providing a plug and play framework it is convenient to have responsive elements with a fixed gain that protects the hardware. Alternatively as shown in section 3.5 or section 4.6 these gains can be chosen to based on the capabilities of the node, and hence are fixed upon manufacture. Provided the gains for the responsive nodes are previously defined, it is useful to find the smallest inertia for which the system remains stable. Thus we can determine the required inertia for the responsive elements implemented. This criteria is shown in Equation 5.13.

$$J > \frac{(D_l + D_g) T}{2} \quad (5.13)$$

Alternatively this requirement (Equation 5.13) could be used to determine the inertia contribution required from each node.

5.2.4 Extended Z-Domain Modelling

The effects of real machine loads and mechanical generation used with electrical generation needs to be taken into account. The element not modelled is the effect of friction and/or continuous droop control. The use of actual machines on the power system driving mechanical loads will generally reduce their power consumption as the frequency and hence rate of rotation changes. This is incorporated into the existing model, shown in Figure 5.6.

Using z -transform tables, the transfer function for $G(z)$ can be shown to be

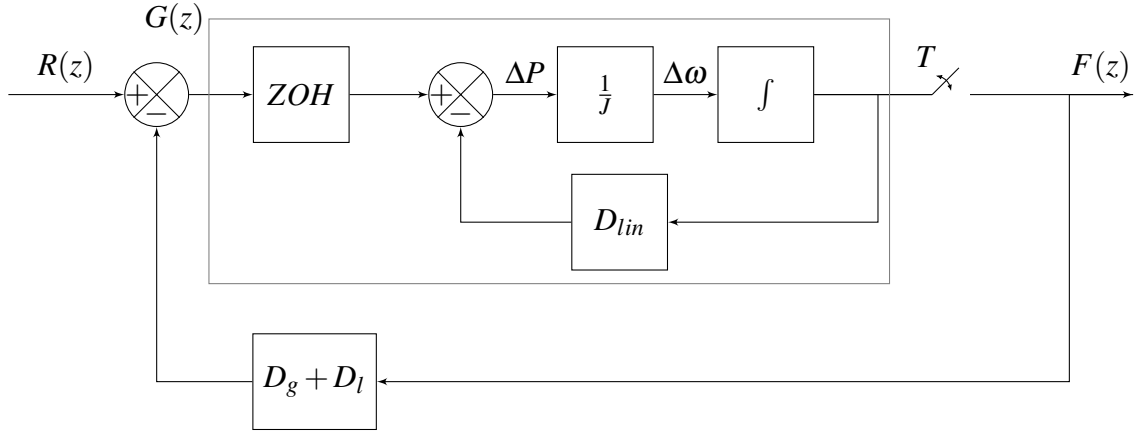


Fig. 5.6 Responsive dynamic modelling in the Z-domain simplified

$$G(z) = \frac{1}{D_{lin}} \frac{1 - e^{-\frac{D_{lin}T}{J}}}{z - e^{-\frac{D_{lin}T}{J}}} \quad (5.14)$$

Making the final closed loop transfer function

$$\frac{F(z)}{R(z)} = \frac{1}{\frac{D_{lin}}{1 - e^{-\frac{D_{lin}T}{J}}} \left(z - e^{-\frac{D_{lin}T}{J}} \right) + D_g + D_l} \quad (5.15)$$

This results in a single pole

$$z = e^{-\frac{D_{lin}T}{J}} - \frac{D_g + D_l}{D_{lin}} \left(1 - e^{-\frac{D_{lin}T}{J}} \right) \quad (5.16)$$

Recall that BIBO stability in the z-domain is predicated on poles being within a unit circle. It can be seen that an increase in $D_l + D_g$ will at some value result in the pole becoming < -1 resulting in BIBO instability.

The interactions between the poles and other parameters is significantly more complex. An alternative representation of the pole is

$$z = e^{-\frac{D_{lin}T}{J}} \left(\frac{D_g + D_l}{D_{lin}} + 1 \right) - \left(\frac{D_g + D_l}{D_{lin}} \right) \quad (5.17)$$

Using L'Hôpital's rule on the pole shown in Equation 5.16 to find the pole for $D_{lin} = 0$ results in the pole

$$z|_{D_{lin}=0} = 1 - (D_g + D_l) \lim_{D_{lin} \rightarrow 0} \frac{\frac{d}{dD_{lin}} \left(1 - e^{-\frac{D_{lin}T}{J}} \right)}{\frac{d}{dD_{lin}} D_{lin}} \quad (5.18)$$

$$z|_{D_{lin}=0} = 1 - (D_g + D_l) \frac{T}{J} \quad (5.19)$$

Which corresponds to the pole determined from the system without a linear droop element shown in Equation 5.10.

Observations

If $D_{lin} = (D_g + D_l)$ the pole is, for all real and positive values of D_{lin} , in the range

$$1 > z|_{D_{lin}=(D_g+D_l)} > -1 \quad (5.20)$$

Further if $D_{lin} > (D_g + D_l)$ then the pole is always within the unit circle for all positive non-zero value of J . Therefore the system will not oscillate with increasing magnitude, provided the linear droop gains are the same or larger than the discretely implemented droops.

In heuristic terms, this can be used to explain why observations indicate a point when the ratio of traditional electromechanical generation being replaced with electronic generation results in unstable behaviour of a system, despite the implementation of droop control.

Further this analysis shows that should linearly responsive nodes be added to the system, the inertia requirements decrease. Hence unknown linear responsive nodes assist in stabilising the power system.

5.3 Modulated inertia

Since inertia can be implemented digitally, it is possible to vary the value. Modifying inertia changes the relationship at which the frequency changes with respect to a change in the loading or generation.

An initial approach may be to use the maximum amount of inertia available. Given the complex dynamics of AC power systems with inductive interconnections, an increase in inertia can result in the deterioration of a systems response to disturbances. An increased inertia will result in a slower response of other system elements. Thus the device implementing inertia will have to have a higher power rating.

It has been posited that an increase in inertia can be beneficial during faults to reduce the magnitude of the swing [104]. In order to prevent instability issues the inertia needs to be reduced following the removal of a fault [134].

Following the logic of the modelling performed in subsection 4.6.3 and subsection 4.6.2 the increase in inertia should ideally be performed alongside with the synchronous decoupling of the power systems. As a result the analysis performed for this section will be performed for single area power systems.

5.3.1 Proposed Inertial Controller

Analysis conducted on the power system model shown in Figure A.8 with discrete droop controllers, in subsection 5.2.3 and proceeding subsections, reveals that there exists an inertia ($J(\omega, t) = J_{const}$) which can be analytically determined for which the system will continue to oscillate. Doubling this will provide the system with a critically damped characteristic. While this analytical technique provides the requirements of inertia, it requires complete knowledge of the entire system to provide an accurate result.

Therefore the goals for an autonomous inertia controller on a stand-alone ad hoc power system are

- Minimal a-priori system knowledge.
- Stable operation with discrete controlled droops
- Scalable linear response, with minimal history required for operation.
- Minimum use of inertia, implying minimum power requirements of synchronous element.

The second last requirement, of a scalable linear response, is to ensure that the inertial devices are evenly loaded during transients as any form of history keeping will result in an uneven inertial distribution and hence uneven loading during a transient.

The final requirement of the controller is to allow for the fastest possible frequency changes under transient conditions. This is essential such that the frequency can change sufficiently for other devices on the power system to notice the change in frequency as soon as it occurs and to take the appropriate steps in a fairly quick manner. This avoids placing large electrical loads on the inertia device. It should be noted that in order to meet this requirements it may be ideal for the controller to select the inertia that is the system's critical inertia. This will allow for stable operation of the system, with the fastest possible frequency response, without unstable oscillations.

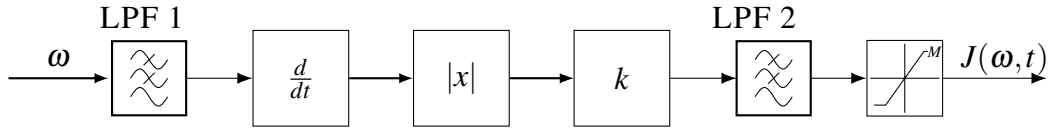


Fig. 5.7 Emulated inertia controller

5.3.2 Controller design

The controller is detailed in Figure 5.7. For any disturbance in the system the emulated inertia will increase to oppose the change in frequency. After the disturbance the system will reach equilibrium and the frequency will stop changing. At this point it is desirable to reduce the emulated inertia again. This results in an inertial controller that will adapt to changes in the number or gain of external droop controllers. It also can be used to determine the critical inertia required to oscillate the power system.

Proof of stability

In the power system as modelled, frequency instability can manifest as one of two situation. In the first situation, the frequency deviates towards an infinite point, indicative of a gross imbalance in generation and load. No finite amount of inertia can prevent an under/over-frequency shut-off from occurring (section 3.5). Therefore this condition is not considered further. The other is an unstable oscillation increasing in magnitude, caused by discrete controller action and insufficient inertia, physical or emulated (subsection 5.2.3).

It can be shown that if the absolute frequency derivative exceeds a constant defined by the discrete controller action (Equation 5.21) in the system modelled by subsection 5.2.3, the system will oscillate between controller bounds and hence eventually result in a over/under-frequency event.

$$\left| \frac{df}{dt} \right| > \frac{f_{max} - f_{min}}{T_{control}} \quad (5.21)$$

Where f_{max}, f_{min} describes the maximum and minimum allowed frequency points and $T_{control}$ is the discrete controller step time. Since the proposed controller increases the inertia for any frequency derivative, it will ensure system stability, provided the gain k is high enough. It is unlikely for a large gain, k , to lead to unstable operation as increasing the inertia to a large value will lead to a slower frequency response.

Perturbing and observing

The perturb and observe element of the controller is inherent in the operation of the controller and system. In order to produce a constant inertia, there needs to be a constant $\left| \frac{df}{dt} \right|$. Since a constant positive $\frac{df}{dt}$ means the frequency is increasing, some external droop controller will eventually respond to the change in frequency. The frequency derivative $\left| \frac{df}{dt} \right|$ is constant if the system frequency oscillates between two points with a constant slope. Therefore this controller will drive the system to the point where the system oscillates.

At the point where $\left| \frac{df}{dt} \right|$ is constant, the inertia output of the controller is constant. The rate of change of the frequency to produce a constant inertia can be described by equation 5.22.

$$\left| \frac{df}{dt} \right|_{const} = \frac{k_{synch}(k_l - k_g)T}{2 * \omega_0} * \frac{1}{k} \quad (5.22)$$

Thus (5.22) can be used to determine the minimum gain required to maintain system operation during steady state. Instability caused by oscillating discrete action, is caused by having the output of the controller oscillating with increased peak magnitude. This occurs with the simple droop controller if the frequency error magnitude increases for each action of the discrete controller. Therefore the maximum allowable frequency derivative of the system is (5.23).

$$\left| \frac{df}{dt} \right|_{max} = \frac{f_{max} - f_{min}}{T_{control}} \quad (5.23)$$

In order to prevent under- or over-frequency cutoffs during any equilibrium point of the system, the maximum derivative should be determined by the worst case equilibrium frequency ($f_{max,equl}$), compared to the maximum frequency limits (f_{max}).

$$\left| \frac{df}{dt} \right|_{max} = \frac{f_{max} - f_{equl,max}}{T_{control}} \quad (5.24)$$

The smallest value of k required to maintain stability can be determined by solving for k using (5.22) and (5.24). Since the best case scenario for a power system is that all nodes; loads, generation and storage are responsive, $k_l - k_g$ can be determined by summing up the total rated power consumption of all devices on a network.

Trade-offs

There are several factors that need to be heuristically accounted for

- Changes in the power system frequency is required for the system to have a non-zero inertia. Therefore it is not possible to have a return to a constant equilibrium frequency. This is an inherent perturbation and response of the controller that may detect changes to the power system.
- Since the power system **does not** return back to the nominal frequency, it is not possible to know whether a change in frequency is to stabilise or destabilise the system. Therefore all changes to the frequency are seen as potentially destabilising.
- Since the inertia is changing, the energy stored in the inertia is changing. Thus the inertial element will consume a net amount of energy that is non-zero.

Additional Elements

The first Low Pass Filter (LPF) in the controller is required to reduce the high frequency noise from the measurement of the rotary speed or frequency. Should too much noise be present in the input to the derivative, the output inertia value will be too high, causing the inertial element to operate at high power levels.

The second LPF in the controller is to limit the speed at which the inertia output may change due to the points where the measured change in frequency is zero.

The saturation element is included to prevent the situation when the output inertia is too low, as well as to limit the maximum inertia of the device according to its rated output.

Disturbance Dampening

The analysis of the behaviour of the controller's behaviour begins with considering the time before a discrete droop controller acts upon the change in frequency. Therefore, the swing equation for a synchronous machine is considered with the droop element D set to 0, for the worst case scenario. In order to simplify the analysis, the absolute function of the controller, is currently neglected. Additionally, the effects of the low pass filters are neglected. The controllers differential equation is presented in (Equation 5.25).

$$J(\omega, t) = k_c \frac{d\omega_m}{dt} \quad (5.25)$$

This is incorporated into the swing equation (Equation 5.26) and solved for $\frac{d\omega_m}{dt}$.

$$P_{in} - P_{out} = J \frac{d}{dt} \omega \quad (5.26)$$

$$\left(\frac{d\omega_m}{dt}\right)^2 = \frac{P_{diff}}{k_c \omega_m} \quad (5.27)$$

In order to solve for $\frac{d\omega_m}{dt}$ it is convenient to note the effect of the absolute function. The absolute function ensures that the output of the inertia controller is always positive. Therefore, for a positive differential power ($P_{diff} > 0$) the change in rotary speed will be positive ($\frac{d\omega_m}{dt} > 0$) and vice versa for negative differential power.

Hence the solution for $\frac{d\omega_m}{dt}$ in (5.27) can be determined to be always real and with the same sign of P_{diff} .

$$\frac{d\omega_m}{dt} = \begin{cases} \sqrt{\frac{P_{diff}}{k_c \omega_m}}, & \text{if } P_{diff} \geq 0 \\ -\sqrt{\frac{-P_{diff}}{k_c \omega_m}}, & \text{if } P_{diff} < 0 \end{cases}$$

This is compared to the synchronous swing equation with constant inertia and $D = 0$ resulting in (5.28).

$$\frac{d\omega_m}{dt} = \frac{P_{diff}}{J_{const} \omega_m} \quad (5.28)$$

Similarities can be drawn between the gain of the inertial controller k_c and the inertia $J(\omega, t) = J_{const}$, when constant. Consider the case when the gain, k_c is equal to the constant inertia J_{const} . In this case the $\frac{d\omega_m}{dt}$ is larger with the controller engaged, for cases where $\frac{P_{diff}}{k_c \omega_m} < 1$. Otherwise the acceleration of the rotary speed is lower than it would be with a constant inertia.

Hence the controller actively assists with the acceleration of small disturbances, to allow for other active devices to more rapidly respond to the disturbance, while slowing down the eventual change in frequency, for larger disturbances.

While this analysis is performed for the case of an islanded remote power system, it is anticipated that this control action will be valuable in assisting with the stability of a grid tied system, as the action of the inertia controller performs somewhat similarly to that presented in existing research.

5.3.3 Test Setup

In order to demonstrate this behaviour a simple single area system was simulated in software and created in a hardware verification platform. This system, comprised of a single inertia emulating element, a single droop generator operating on a discrete basis and a generator injecting a disturbance as demonstrated in Figure 5.8. This is modelled as shown in Fig-

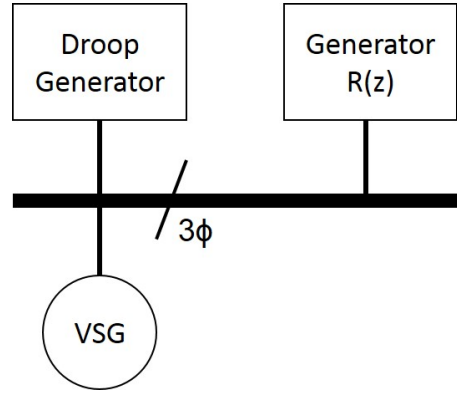


Fig. 5.8 Test configuration to demonstrate instability issues related to inertia

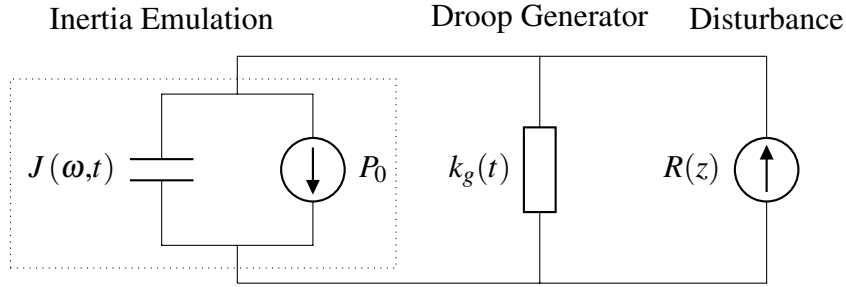


Fig. 5.9 Modelling of test setup

Figure 5.9. Where $J(\omega, t)$ is the emulated inertia as a function of time and frequency, P_0 is the load requirements of the inertia emulation (0 W for software, $\approx 1,4$ kW for the hardware emulation, see subsection A.6.3). An inverter emulated the bidirectional droop generator which responded every 1 second, with a gain of $k_g = 1$ kW/Hz. A second inverter $R(z)$ supplied a 0,5 kW disturbance every 30 seconds, with the hardware emulator adding a constant 1,0 kW generator to assist with the load.

The inertia controller was set with a gain $k_c = 100.0$ and a filter bandwidth on both filters (pre and post) to 2,0 rad/s

Addition of generation

The correct usage case for the controller is the situation when generators are added or removed from the system. In this simulation the gain, k_g , of the responsive element is increased from 2 kW/Hz to 5 kW/Hz at time $t = 50$ s. A disturbance of 500 W is added and removed every 30 seconds to provide system stimulation.

Under a constant emulated inertia of $J_{const} = 5,0 \text{ kg} \cdot \text{m}^2$, shown simulated in Figure 5.10 the system demonstrates almost ideal, critically damped characteristics until the additional

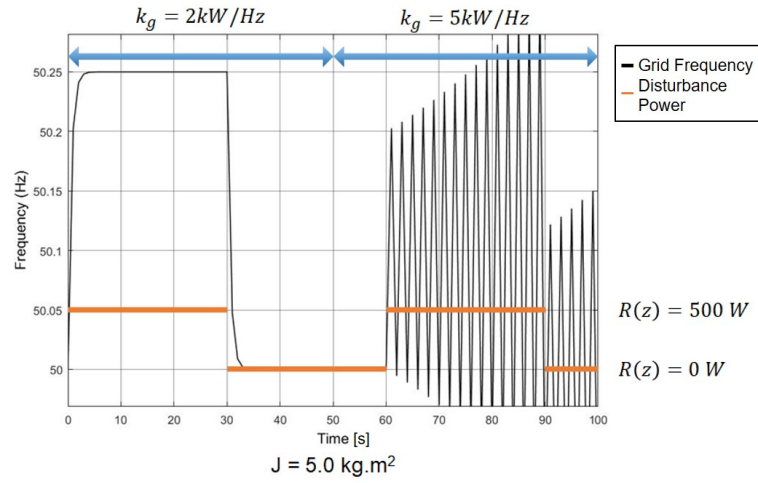


Fig. 5.10 Software simulated frequency response after a change in the droop gain at $t = 50$ s with inertia ($J_{const} = 5,0 \text{ kg} \cdot \text{m}^2$)

droop gain is added at 50 s. Thereafter the system begins to oscillate with increasing magnitude. This was verified with the hardware based remote power system simulator (Figure 5.11). Due to continuous droop action and other non-ideal effects (see section A.9), the emulated inertia was lowered to $J_{const} = 2,5 \text{ kg} \cdot \text{m}^2$ to reproduce the software simulated results. It is noted that the frequency oscillations lead to an under-frequency cut-off at $t \approx 54$ s, at which point the system simulation is stopped to prevent equipment damage.

With the emulated inertia controller enabled the frequency response, shown in Figure 5.12, is more dampened. After the change in the droop gain, the system maintains stability through the transient, with no overshoot. The inertia used during the 500 W disturbances, shown in Figure 5.13, is significantly higher, but this is to be expected as the disturbance is assumed to be a potentially destabilising event. After the transients the emulated inertia actually returns to a lower inertia value, than was used in the constant inertia simulation.

When repeated on the hardware based remote power system simulator, shown in Figures 5.14 and 5.15, similar results are noted. The increased noise present on a real system is noted to be relatively large, which is obscuring certain features. It is noted that the frequency does oscillate after settling to the new equilibrium point with a more damped response to the disturbances. The inertia does increase during the 500 W disturbances provided every 30 s and decreases thereafter. The mean of the emulated inertia controller following the change in the droop gain does increase proportionally to the increase in the droop gain. This is similar behaviour to the software simulation and is expected from the model (Figure A.8). Most importantly, the system does not oscillate with increasing magnitude towards a frequency limit despite the change in the droop gain.

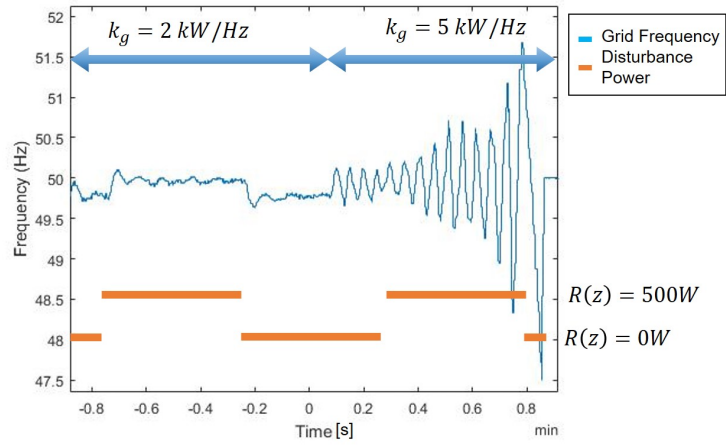


Fig. 5.11 Hardware simulated frequency response after a change in the droop gain at $t = 0$ min with inertia ($J_{const} = 2,5 \text{ kg} \cdot \text{m}^2$)

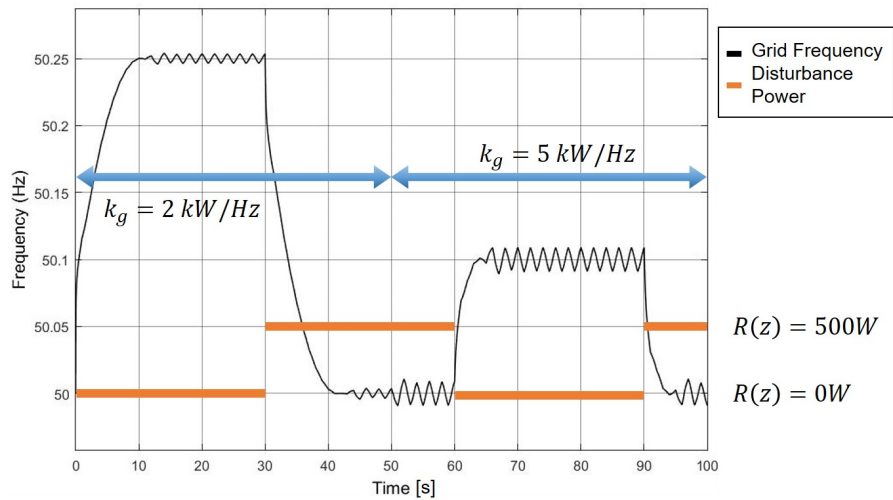


Fig. 5.12 Software simulated frequency response after a change in the droop gain at $t = 50$ s with emulated inertia control

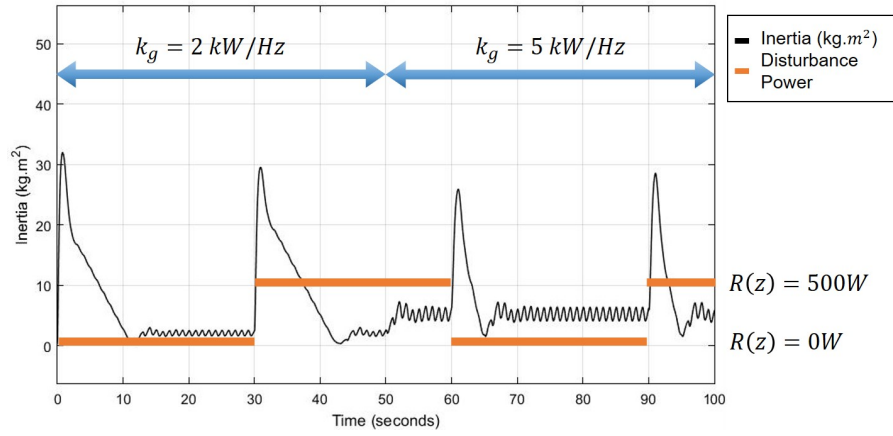


Fig. 5.13 Software simulated emulated inertia, $J(\omega, t)$, after a change in the droop gain at $t = 50$ s

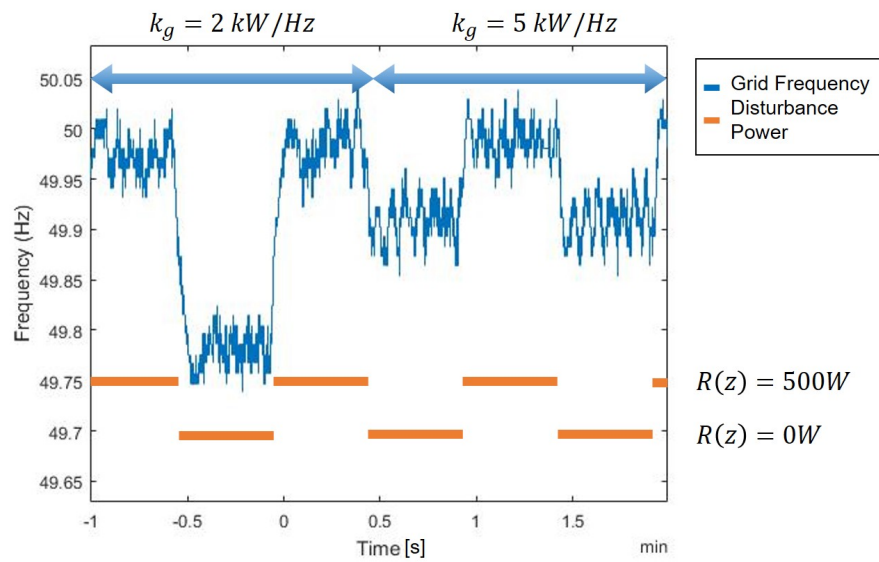


Fig. 5.14 Hardware simulated frequency response after a change in the droop gain at $t = 0$ min with emulated inertia control

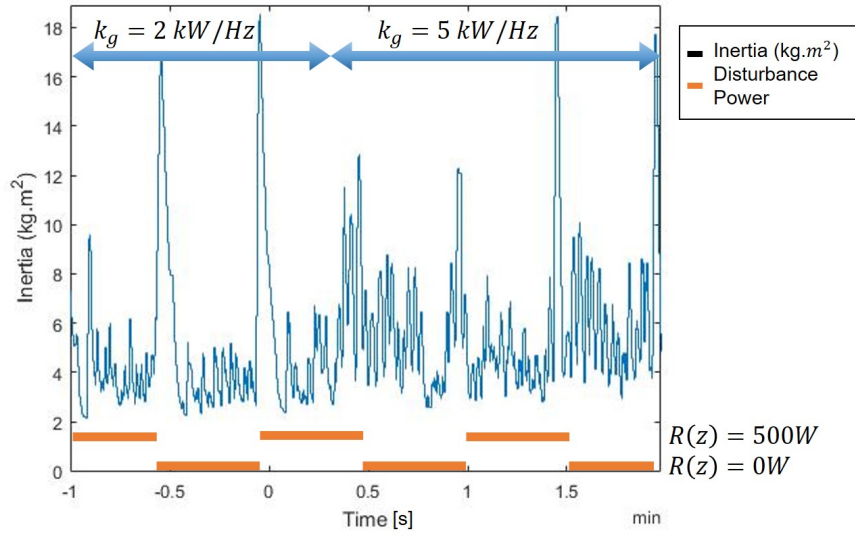


Fig. 5.15 Hardware simulated emulated inertia, $J(\omega, t)$, after a change in the droop gain at $t = 0$ min

5.3.4 Practical Considerations

Considering the relatively low rate at which generators will be added or removed on an actual power system, it may not be feasible to operate the inertial controller continuously. In this situation, the output from the inertial controller under steady state conditions can be used to determine the critical inertia requirements, J_{crit} , of the power system about which the system will oscillate. This value can then be doubled (as a conservative estimate) and applied as a constant value for the virtual synchronous generator. Since a reduction in droop gain reduces the inertial requirements of the power system, this fixed value of inertia will maintain grid stability. In the event that the droop value will be increased due to a change in the power system components, then the controller can be manually activated and the process repeated.

Non-linear droop actions, such as those used to provide priority for different loads and generators due to operating costs, thermal loads with digital (on/off) control etc can result in instability in particular operating regions. These can include polynomial or other more complex functions for a droop response. The adaptive behaviour of the controller presented can theoretically ensure stability against unstable oscillations due to feedback delays.

The time taken for the frequency to be measured has been demonstrated to be a significant influence to the required inertia. Established power systems possess large amounts of inertia and hence the requirements on frequency measurement dynamics were quite low. Implementing inertia on inverters requires additional storage to be added which increases cost. Faster

frequency measurement or tracking techniques could reduce the inertia storage requirements such that they can be met with already present storage used in inverter designs [151].

5.4 Conclusion

Presented in this chapter is dynamic power flow analysis for single area systems, considering the non-ideal effects of lower cost responsive nodes. In the proposed power systems with no regulation, this modelling accounts for a majority of the small signal stability issues observed in the power system simulation. While describing delays as linear delay may be initially sufficient, it is preferable to more accurately model the system using the z-domain. This is due to the recently more common, inherently discrete means of measuring frequency. This modelling was confirmed with simulations run on the power-hardware-in-loop simulator. This modelling predicts the conditions that can lead to unstable oscillations of the power system due to the delayed response of participating nodes. It could be shown that in order to ensure stability, the responsive elements need to respond quicker, or the system requires more inertia, or a combination thereof. In the interests of plug and play system operation it is ideal that the system inertia be automatically determined. A controller was designed which achieves this objectives in the software and software simulations. This modelling provides either a way for the appropriate amount of 'inertia' to be preset within an inverter or adaptively changed during operation of the power system.

Chapter 6

Case Study

6.1 Introduction

To demonstrate the use of the principles and modelling presented herein, some scenarios will be demonstrated. These will demonstrate the plug and play and expandable capabilities of the system developed using the presented modelling. These scenarios focus on the autonomous active power dispatch capabilities of the system under anticipated usage conditions.

All demonstrations will include cases of excessive generation, where balanced loading of generation needs to occur in the presence of autonomous active power dispatch. These demonstrations are conducted on the power hardware-in-loop simulator described in appendix A. This is a real non-ideal system consisting of controllable loads and generation and non-ideal factors, explained in appendix A. Operation of the proposed methodology within this non-ideal environment provides a high level of confidence in its practical deployment.

For all the tests the frequencies for the decentralised response, as described in Figure 3.2, was set to:

$$\begin{aligned} s_{max} &= 52 \text{ Hz} \\ s_1 &= 51 \text{ Hz} \\ s_0 &= 50 \text{ Hz} \\ s_{-1} &= 49 \text{ Hz} \\ s_{min} &= 48 \text{ Hz} \end{aligned} \tag{6.1}$$

The solar panels are set to reduce their energy output according to Equation 6.2 which was calculated every 100 ms. This was done to prioritise the output of the solar panels.

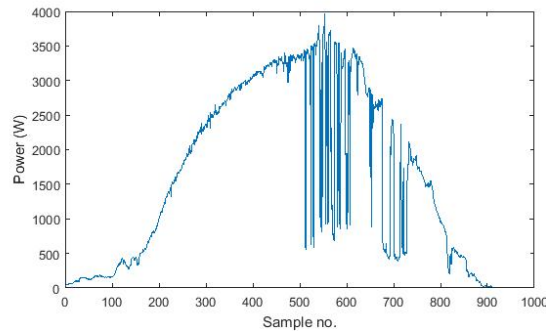


Fig. 6.1 Reference solar power used for the emulation of solar generation. See section A.10.1

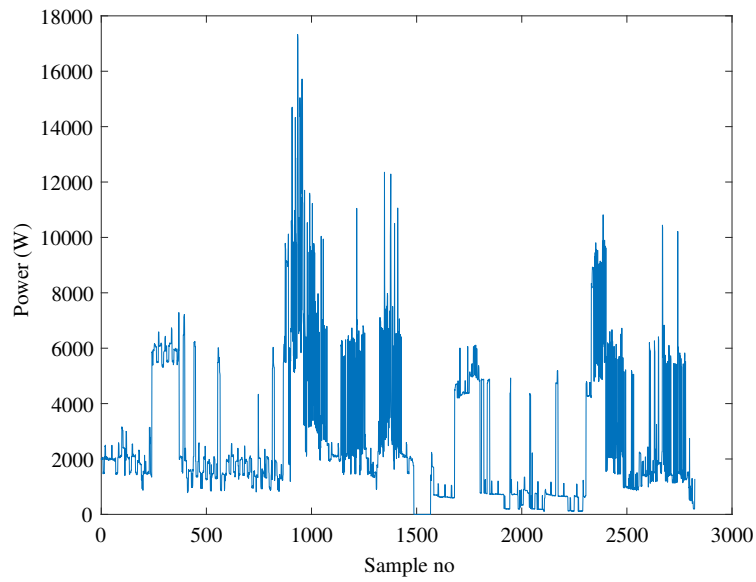


Fig. 6.2 Reference load power used for the emulation of a variable load. See subsection A.10.2

$$P_{out} = P_{sample} \begin{cases} 1, & f_{grid} \leq s_1 \\ \frac{f_{grid} - s_1}{s_{max} - s_1}, & s_1 < f_{grid} \leq s_{max} \\ 0, & f_{grid} > s_{max} \end{cases} \quad (6.2)$$

The reference solar profile used for these generators is presented in Figure 6.1.

The reference load profile used for load emulation is presented in Figure 6.2.

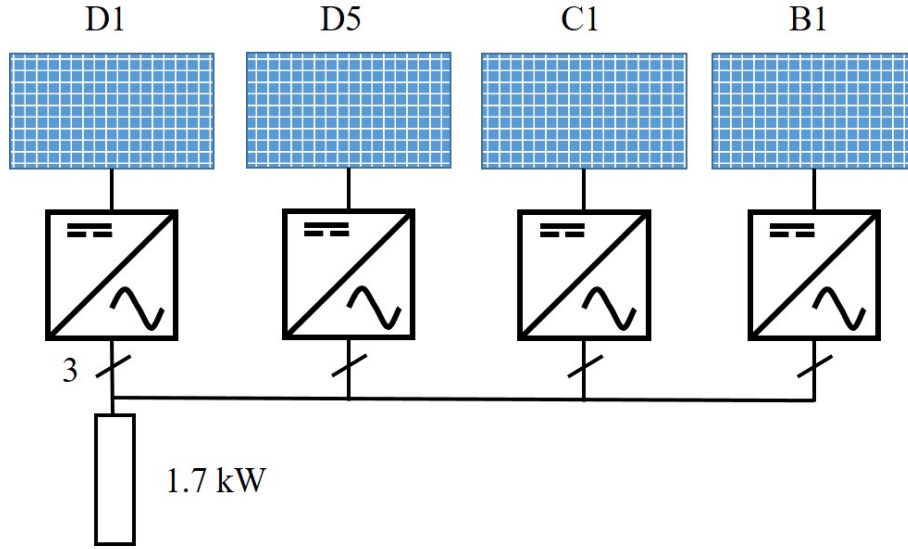


Fig. 6.3 Diagram of simulated experiment with only solar panels

6.2 Solar alone

This test demonstrates the ability of the system to operate without any form of storage, using stochastic solar generation alone, illustrated in Figure 6.3. The purpose of this test is to show that with the principles as demonstrated multiple solar sources can be used, added and removed to power a single load without requiring storage. This demonstrates a minimal entry level system which can be later expanded with additional generation or storage. System blackouts are expected on a system without storage and with non-responsive loads where total load can exceed total generation.

The load in this case is the synchronous machine's integral fan and brushless exciter, of approximately 1,7 kW (section A.6). The droop of the synchronous machine was linearly controlled to only operate from below 48 Hz. Therefore electrical load on the system would be 0 at a minimal frequency of 47 Hz (with $f_{lim} = 48$ Hz, $f_{dev} = 1$ Hz, $k = 14$ N·m/Hz equivalently 1,7 kW/Hz, section A.11). Therefore, the electrical load of the synchronous machine is constant $\approx 1,7$ kW for frequencies over 48 Hz. This allows the system to continue simulation despite being in a blackout condition. It is not possible to fully simulate blackout conditions as this would require operating the elements far outside their operation regions (see Table A.4 and Table A.7).

The system consists of four variable power sources and the synchronous node, which also provides the base load, connected as in Figure 6.4. These systems are connected via low-impedance lines.

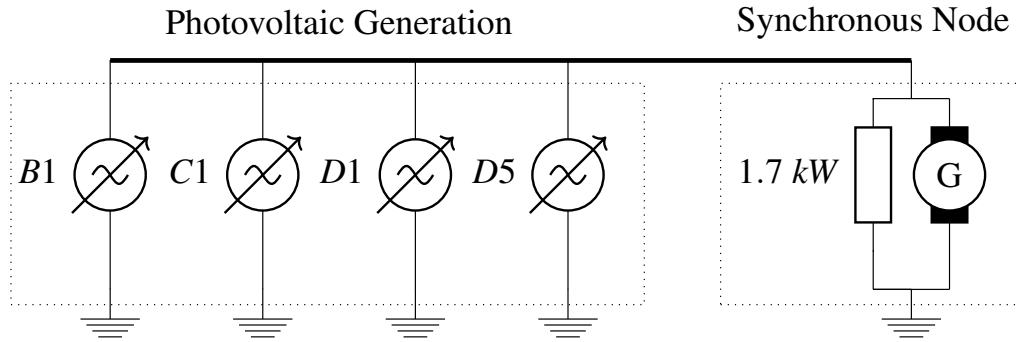


Fig. 6.4 Single line diagram of simulated system comprising of photovoltaic generation (B1,C1,D1,D5) and inertial element, combined with the load.

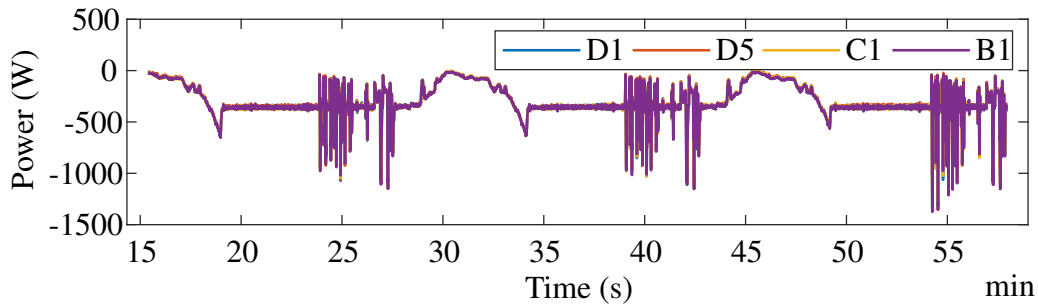


Fig. 6.5 Active power of nodes B1, C1, D1 and node D5

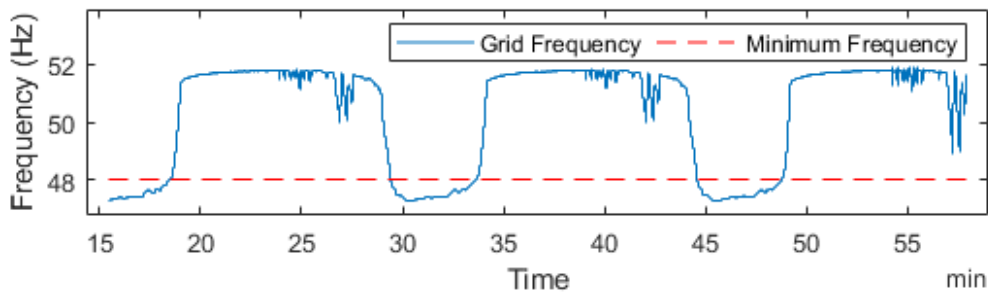


Fig. 6.6 Grid frequency during tests.

Figure 6.5 shows the power output of the four photovoltaic generator emulators during this test. Figure 6.6 shows the grid frequency during this test. Due to the lack of storage there did exist times when the grid frequency would drop below 48 Hz. At this point the synchronous node implemented a droop response as described in section A.11. These are times when an actual system would be in a blackout or black start condition due to total load being larger than total generation.

Despite the presence of these overloaded conditions, the system still adequately dispatched the correct power to the load, when sufficient generation was available. All nodes

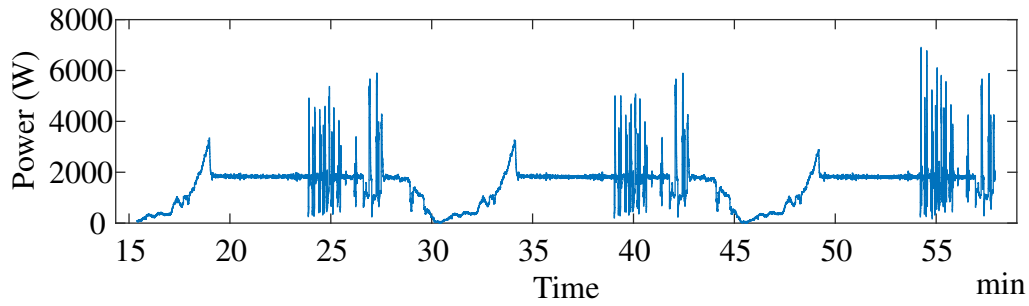


Fig. 6.7 Electric power consumed by the synchronous node

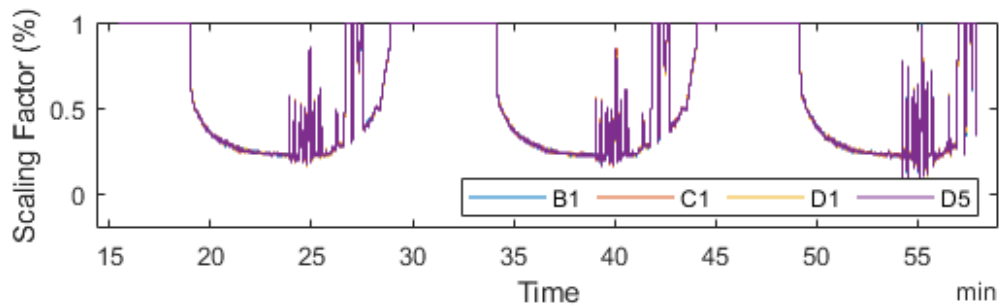


Fig. 6.8 Generation reduction factor of nodes B1, C1, D1 and D5

autonomously dispatched similar power output resulting in equal loading. During conditions of reduced photovoltaic generation, the frequency did decrease. During these times, the total load was initially supplied by the inertial element.

The reduction in the synchronous node load during overload conditions is shown in Figure 6.7. Below the nominal value of 1,8 kW for extended periods the droop response of the synchronous node is in use. The fluctuations of the electrical loading are due to the inertial response of the synchronous node.

The reduction factors of the photovoltaic generators is shown in Figure 6.8. These factors are similar for all generators during the experiment indicating that all elements were loaded equally.

The difference in inertia loading during the third photovoltaic cycle is due to a change in the emulated inertia, documented in Figure 6.9.

The voltage of phase A of the synchronous node is included for transparency in Figure 6.10. These voltage spikes can be attributed to the relatively slow response of the PID controller for the excitation. Fast non-ideal frequency/rotary velocity transients (section A.9) of the synchronous machine do lead to spikes in the voltage.

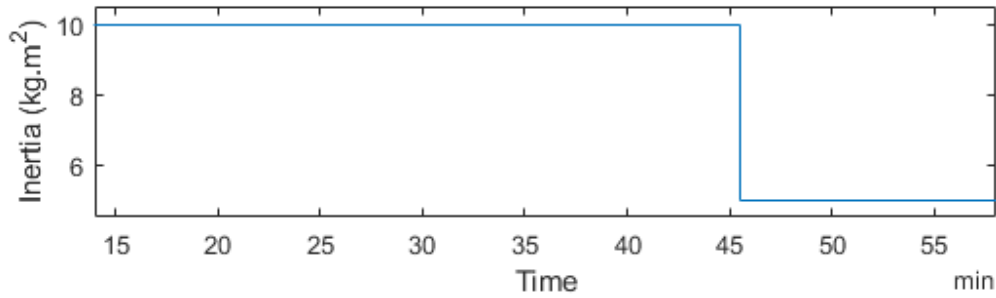


Fig. 6.9 Emulated inertia

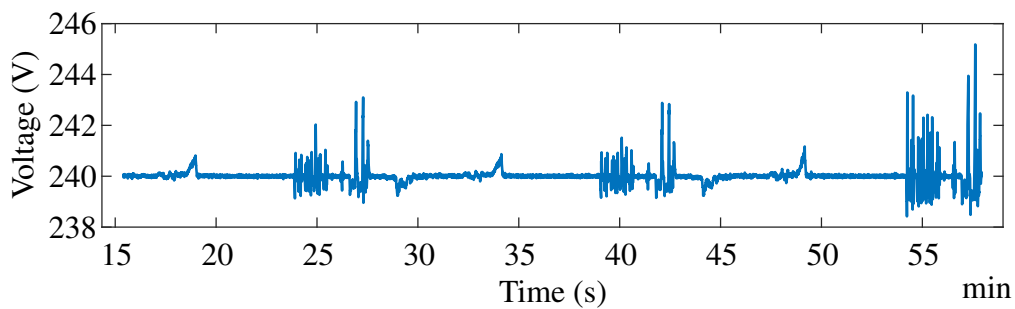


Fig. 6.10 Phase A voltage magnitude during simulation

6.2.1 Removal/addition of generator

To demonstrate the plug and play nature of the system, it was initially operated with nodes D1 and D5 only. Node C1 was then enabled, followed by node B1. This is illustrated in Figure 6.11.

The power produced by the nodes is shown in Figure 6.12. The non-ideal start-up power consumption of the nodes causes the positive power consumption of the node, before the node starts to generate power (C1 at 170 min, B1 at 181 min). The grid frequency is shown in Figure 6.13.

There exists a period of low generation due to the afternoon cloud of the playback data (Figure 6.1, from sample 500), that occurs in the experiment at times; 164 min, 178 min and 192 min. As additional generators are added, it can be seen that the system is better able to ride through the reduced generation condition as the frequency barely drops below the minimum frequency limit. This demonstrates the systems ability to appropriately scale as more generators are added.

Further it is noted that as generators are added the load upon each generator scales appropriately, to ensure that all generators are equally loaded. This is noted in the behaviour of the scaling factor shown in Figure 6.14.

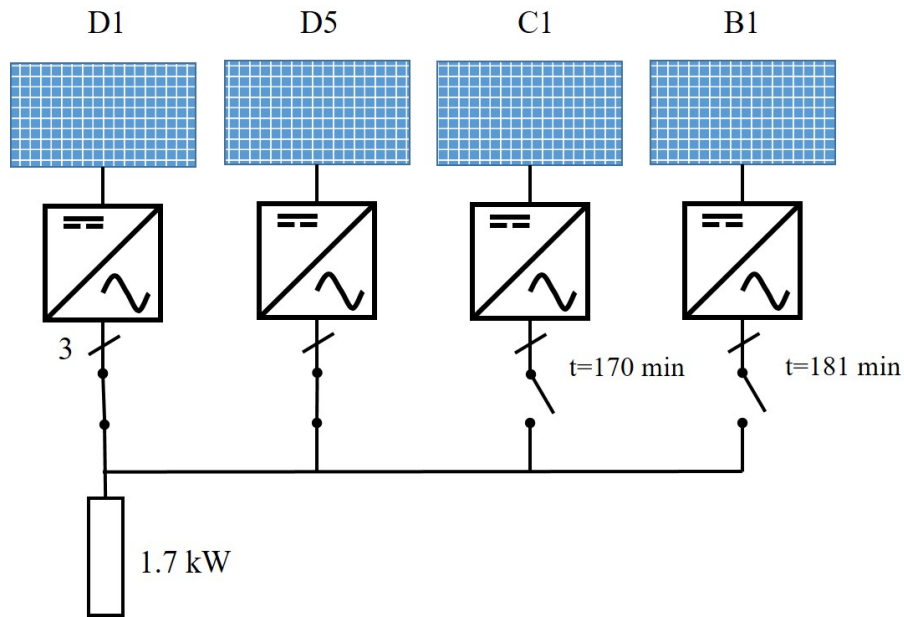


Fig. 6.11 Diagram of simulated experiment showing the addition of solar panels

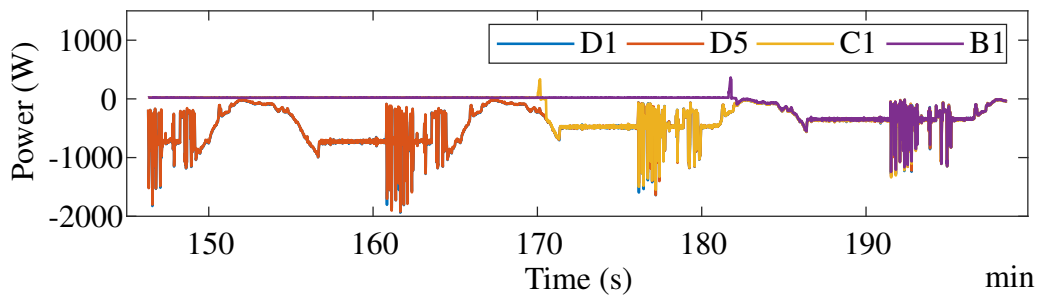


Fig. 6.12 Active power of nodes B1, C1, D1 and node D5

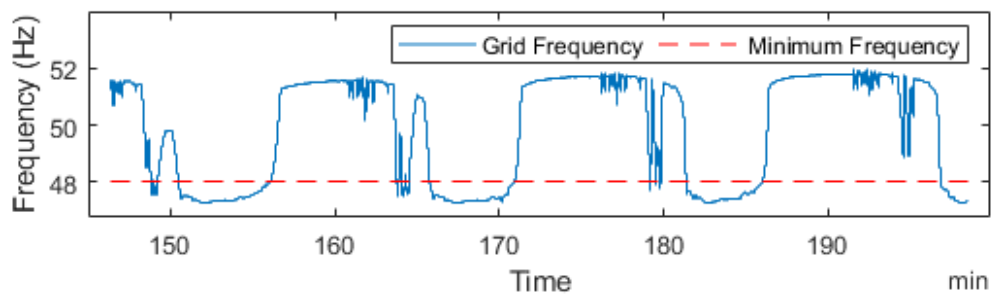


Fig. 6.13 Grid frequency during tests.

While generators are added, the power going to the synchronous node (Figure 6.15), remains fairly constant. The down time, time when the frequency goes below the minimum frequency threshold, is reduced as generators are added.

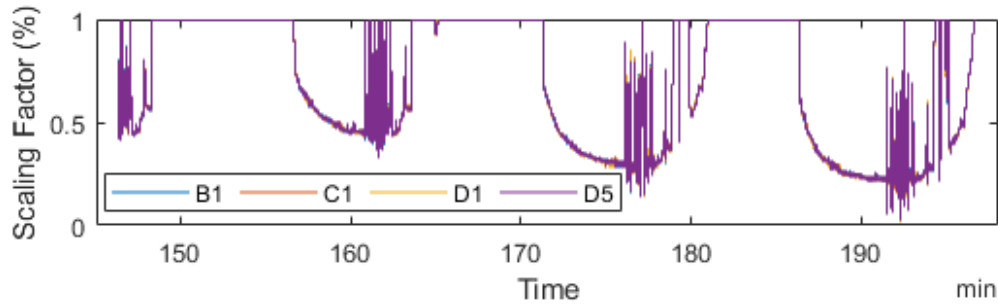


Fig. 6.14 Generation reduction factor of nodes B1, C1 and D1

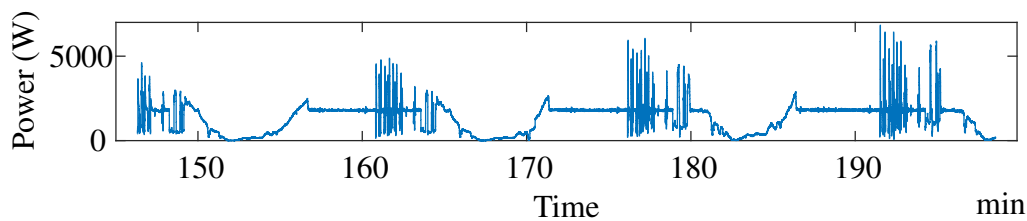


Fig. 6.15 Electric power consumed by the synchronous node

6.3 Solar with a storage node

This test demonstrates a more common scenario, which is the use of solar panels with some load, illustrated in Figure 6.16 and detailed in Figure 6.17. This allows users to access ecologically clean solar energy while using loads during the equivalent night-times. This is anticipated to be the common use case for these systems.

The load for this demonstration is both the synchronous machine's integral fan and brushless exciter, of approximately 1,7 kW (section A.6), as well as an additional load profile (Figure 6.2).

The solar generation was emulated with 3 nodes emulating the solar panel profile (section A.10.1). Due to the lower time frame of the simulation, the energy storage was set to an energy value of 1 kW · h. The maximum power of the storage node was set to 2,5 kW, which could be exceeded by the maximum solar panel generator. The storage node was controlled to respond only once every second.

Total system inertia was set to a constant 10 kg · m².

Figure 6.18 shows the power output of the solar panels and the power consumption of the variable load. Figure 6.19 shows the power absorbed and supplied by the storage node.

During the first day, during times when the solar is more than the total load (approximately minutes 5 to 10) the storage node autonomously changes to charging state, absorbing the excessive power available from the solar nodes. When the solar power output decreases,

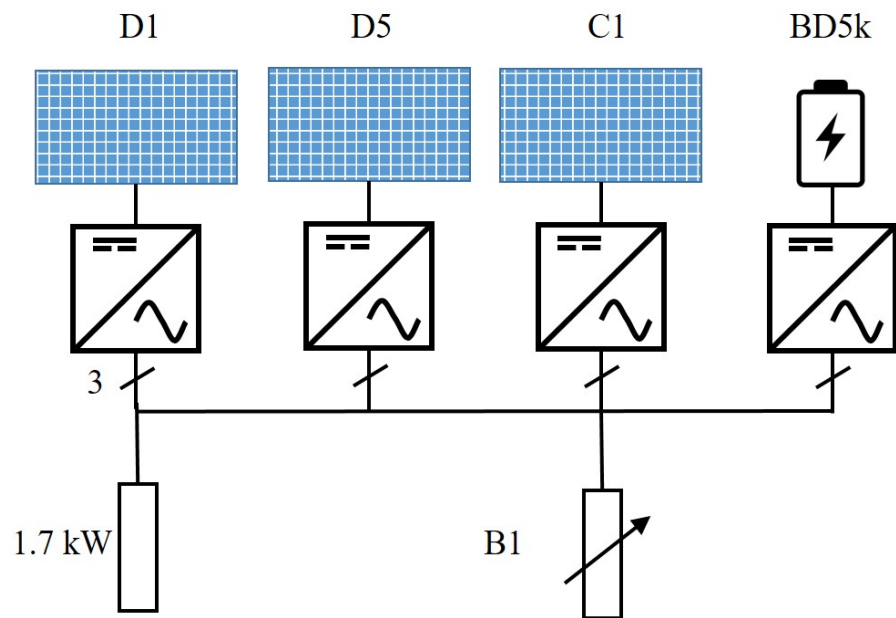


Fig. 6.16 Diagram of simulated experiment of solar and a storage element

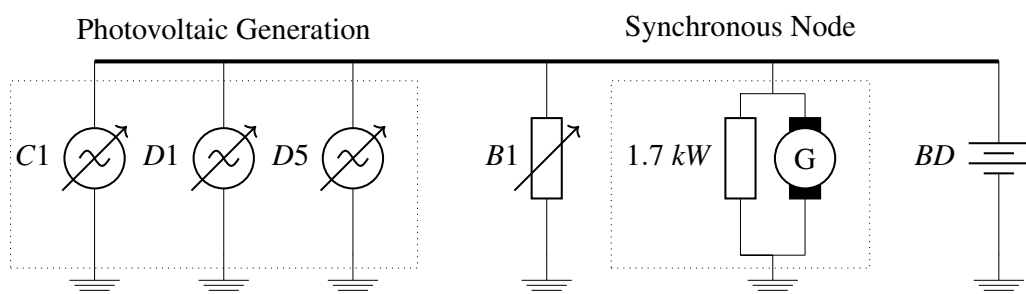


Fig. 6.17 Single line diagram of simulated system comprising of photovoltaic generators (C1,D1, D5), storage (BD), inertia and load (B1).

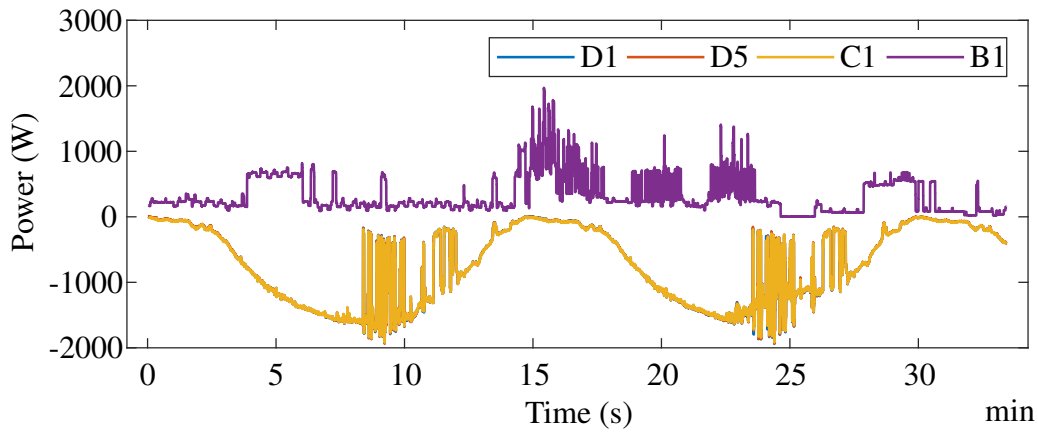


Fig. 6.18 Active power of nodes B1, C1, D1 and node D5

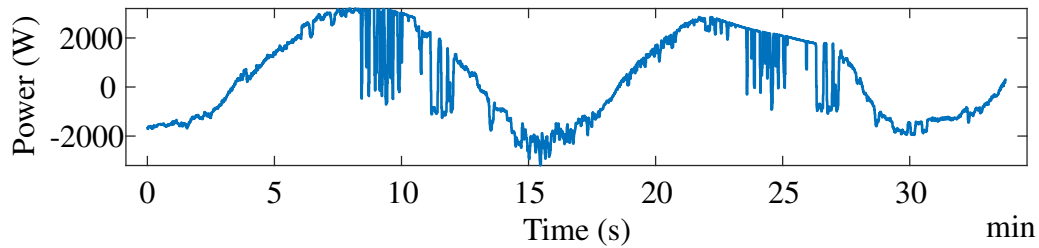


Fig. 6.19 Active power for storage node

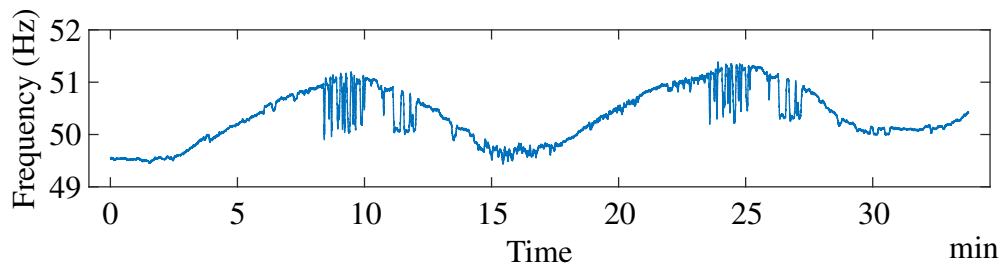


Fig. 6.20 Grid frequency

the storage node decreases its charging power. Note that when the solar panel output is essentially 0 W the storage node supplies the power required by the loads.

Figure 6.20 shows the measured grid frequency during the simulation. Figure 6.21 shows the energy stored in the storage node.

During the second day, the storage node starts to indicate that it is charged, by reducing the active power it draws from the grid (at minute 22). This results in an increase of the power system frequency. The solar panels likewise start to curtail their generation (by the

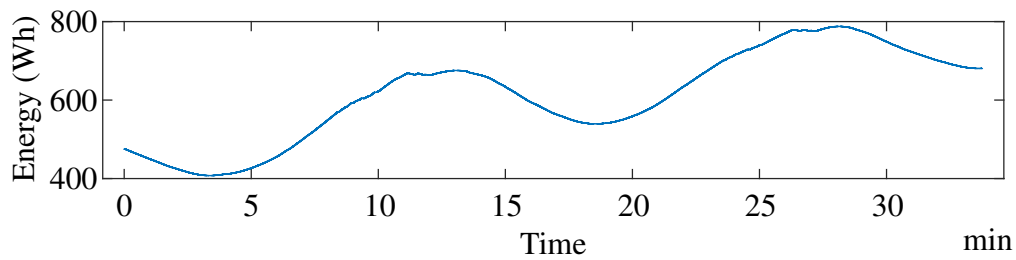


Fig. 6.21 Energy state of the storage node.

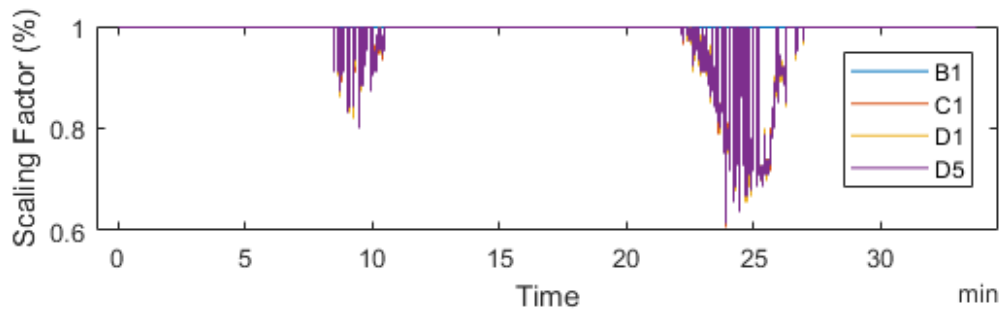


Fig. 6.22 Generation reduction factor of nodes B1, C1 and D1

factor shown in Figure 6.22) to prevent an over-generation state. Of note is that all solar panels decrease their power equally sharing the load.

During the first solar cycle it can be seen that at the peak of solar generation was curtailed due to the storage node operating at its maximum power.

This demonstration shows that using decentralized operation principles, it is possible to incorporate a storage system with a finite energy storage value and maximum power limit. The storage node is able to autonomously decide to charge or discharge based on its own observations of frequency alone. The solar generation nodes decrease their active power dispatch to avoid the storage node from becoming overloaded, or overcharged. While the solar nodes are decreasing their active power they do so equally, ensuring that they are loaded equally.

The phase A voltage of the synchronous node is included in Figure 6.23. The power consumed by the synchronous node, while emulating inertia is shown for transparency in Figure 6.24. Although the active power of the synchronous machine does show large peaks, this is due to the relatively large inertia response in addition to the loading. It is also noted that the grid did not experience any brownout conditions.

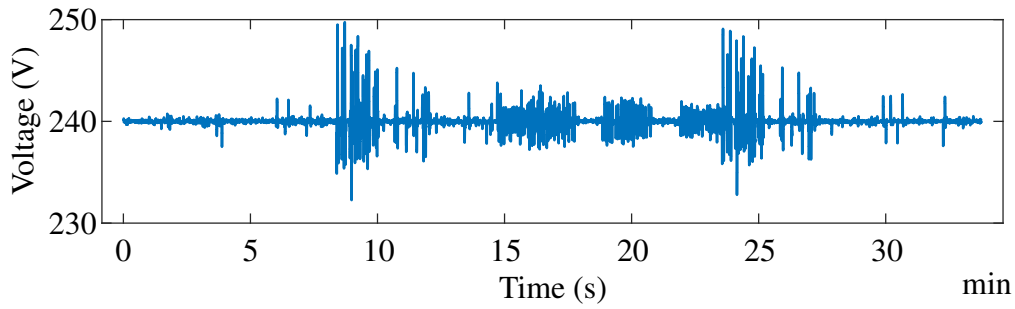


Fig. 6.23 Phase A voltage magnitude during simulation

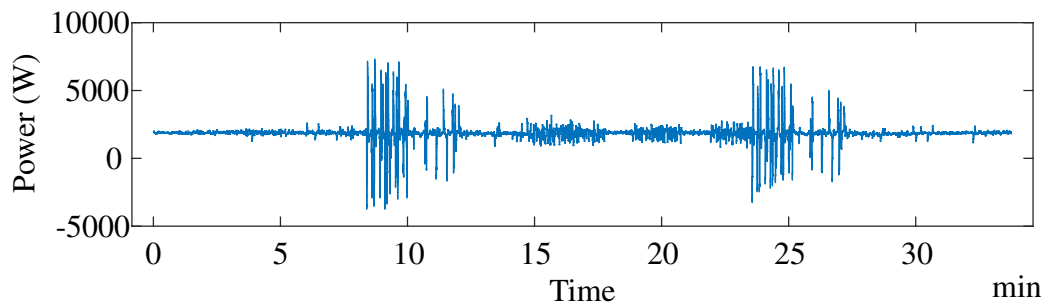


Fig. 6.24 Electric power consumed by the synchronous node

6.4 Analysis

These demonstrations show the robustness of operating a power system according to the modelling and rules outlines in the research. By applying a common set of rules that all nodes obey, a robust plug and play system is realised. The system autonomously realises balanced dispatch of power, both with and without a storage element. Realistic elements such as power and charge limits on the storage system can be easily incorporated.

A system designed using these rules may not make optimal usage of all resources. However, it benefits from the robustness and scalability of a plug and play system.

The constant inertia selection for these demonstrations was chosen to ensure continuous operation, for the worst case scenario of all nodes active. Although ideally the inertial emulation should be incorporated in each element, with each element emulating the inertia it requires, the experiment hardware is unable to emulate this behaviour.

6.5 Conclusion

Demonstrated in this chapter is the anticipated deployment of a system in a real world scenario. At first a single solar generator is utilised with additional solar generators being

added in subsection 6.2.1. This inherently leads to scenarios where a blackout would occur. In order to ensure a more reliable supply of power, a storage system was added to the existing system in section 6.3, improving the energy reliability. Despite the fact that the system dramatically changed between the scenarios, no additional configuration was needed provided all nodes were pre-configured using the predetermined states of Equation 6.1. Therefore, decentralised management of energy dispatch can be achieved with plug and play power systems.

Chapter 7

Conclusions and Recommendations for Further Work

7.1 Summary

The objective of this research was to investigate the possibility of realising plug and play power systems with a high penetration of renewable energy sources. Following an analysis of contemporary literature a deficiency was noted. The rigid modelling and control techniques applied to existing power systems does not allow for ad hoc and expandable power systems to be created. This is largely due to the legacy development of the existing power system. The highly hierarchical nature of legacy power systems is largely incompatible with modern distributed generation. Current means of operating the power system, due to historical limitations do not allow for the creation of a scalable power system.

Starting from a heuristic foundation of any power system, several basic requirements were identified. These were extended by the incorporation of priority generation and loads. This provides a power system with a means of selecting certain cheaper (ecologically or economically) sources over others. This analysis provides a theoretical foundation for the design of all power systems by obeying the conservation of energy principle.

Thereafter, expandable DC supplies were investigated. It was noted that the most low-cost means of scaling DC power supplies was the passive paralleling technique. The dynamics of the resulting circuit is the same as the AC swing equation. This allows for the complex components of AC power dynamics to be captured simply with an equivalent RC circuit. This analysis allowed for the effects of inductive transmissions lines and secondary response to be analysed in the context of a scalable system of unknown size. Based on the premise that an network of an unknown number of resistors and capacitors is always stable it is

desirable that components behave under this model as resistors or capacitors. It is shown that both inductive transmission lines and secondary response cannot be used in a scalable system, unless sufficient system planning is performed. The modelling developed utilises simple passive circuit components, reducing the complexity of its analysis and hence required knowledge needed to be able to maintain and analyse these systems.

The modelling produced was then extended by incorporating the non-ideal effect of discrete and continuous delays to the operation of the power system. This resulted in a few unstable regions where following a disturbance a system may oscillate with increasing magnitude. This reinforced the results of existing literature in showing that a sufficient amount of inertia, whether synthetic or physical, is required to prevent this unstable behaviour. This assists with the requirements of inertia in resistive low-voltage power systems, to maintain the power-frequency relationship. This demonstrates the importance of inertia in modern power systems.

The results of this modelling was then verified within a hardware based power system simulator. Using actual off-the-shelf power inverters to emulate the behaviour of photovoltaic and storage elements, various scenarios where nodes were added or removed from the power system were demonstrated. This verified that the behaviour of the system, designed as described herein, remained stable with or without energy storage elements, in the presence of the addition and removal of generation resources or loads.

7.2 Summary and Main conclusions

Following the review of existing literature, the research objective was to create a modelling paradigm that enabled the creation of scalable AC power systems. Due to similarities between the dynamics of a DC and AC power system, the power to frequency relationships of an AC power system can be modelled as a set of resistors and capacitors. Ideal required dynamic responses of elements on a power system were then determined. Modelling was extended by incorporating delays inherent in the operation of digitally controlled power system elements. This demonstrated a reliance of the power system on system inertia, whether virtual or physical. An inherent result of the modelling is a theoretical premise on which scalable AC and DC hybrid systems can be interconnected as desired. Since inertia can be synthetically implemented and hence varied, a controller which autonomously adjusted the inertia to prevent increasing oscillations in the system as designed was demonstrated.

The result of this modelling was then verified on a non-ideal hardware simulator. The results verified that by following the grid modelling performed, it is possible to autonomously dispatch active power in a plug and play, three-phase AC power system using decentralised means. This enables the affordable and reliable ownership and operation of renewable energy power systems at a household level.

7.3 Recommendations for further work

- The development of black starting protocols. Limitations of the equipment used (mainly an existing voltage and frequency source) meant that experiments assumed the initial existence of a power system. In reality, it is likely that a stand-alone power system will experience blackouts and as a consequence require black start protocols. An initial idea, may be the utilisation of a low-frequency, low voltage condition that other inverters can observe and hence assist with the black starting of a power system in the presence of unresponsive loads.
- The development of protection protocols. A power system that consists primarily of electronic generation will not possess the fault currents that rotating machine based power systems benefit from. Hence, existing protection principles are unsuited for developing power systems. For example the control of an inverter can operate significantly faster than a mechanical switch. It is required to investigate and establish appropriate protection protocols and devices.
- The implementation of these concepts on dedicated hardware. While efforts were made to implement these grid control concepts in an actual inverter, limitations in the available hardware made this task particularly difficult. While these concepts are hardware verified, the establishment of an actual power system, consisting of dedicated hardware will allow concepts, such as black starting and protection to be investigated with minimal legacy interference.
- AC and DC system interactions (AC/DC super-grids, hybrid/meshed grids). Three-phase AC is typically more suited for power ranges of 2 kW and higher. At lower power levels, DC or single phase AC is more applicable. The modelling performed herein provides a theoretically starting point for the establishment of AC or DC power systems, and the interconnection thereof. Actual implementation of either system would be a monumental step towards the realization of scalable hybrid power systems.

While this research is targeted towards areas with little to no existing infrastructure, AC/DC super-grids may be useful for existing and future power systems in more developed locations.

- Gaming as a means of energy management algorithm development. There exist a plethora of resource management computer games, wherein players have to manage their resources. These games penalize players if they do not effectively match resource generation to supply in real-time. Games such as *Supreme Commander*, *Factorio* and many more, force players to creatively micromanage their finite energy resources. There exist many strategies regarding how best to manage your resources in these games, which are discussed and debated in on-line forums. It is suggested that existing game originating strategies may be useful in future grid systems. Further the design of a game with more realistic resource management concepts may allow people, without detailed and specialized understanding of power systems, to contribute towards a more sustainable future. This may also aid public education on finite energy and resource management topics.

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Appendix A

University of the Witwatersrand's Power-Hardware-in-Loop Power System Simulator (WPHS)

A.1 Introduction

While software simulation is a useful tool for the safe and fairly accurate modelling of power systems, it is limited by the detail that can be captured and reproduced in the base model. On the other hand, the cost and complexity of implementing actual field trials is impractical for the experimental development of new grid control theories and ideas.

It is therefore desirable to utilise a combination of software and hardware systems to emulate a power system. This will allow for the reproduction of a combination of real world effects, such as measurement noise, errors etc, in a reproducible environment. Being able to reproduce weather patterns for wind and solar based generation while adjusting power system parameters with a real system provides authentic verifiable results.

The WPHS is constructed using off-the-shelf industrial machine drives and machines. This includes a selection of 4-quadrant and 2-quadrant variable speed drives. The drives are controlled via PLCs that receive commands from a central computer via Modbus TCP.

In this appendix, the design and non-ideal affects of the power-hardware-in-loop simulator are explored. First the setup of the power interface hardware and feedback is defined.

Thereafter, the synchronous node which provided frequency and voltage control is presented. Then the nodes which make up the majority of power interfacing hardware is shown, with their static and dynamic power qualities. Analysis is performed in an attempt to quantify the reactive power characteristics of the hardware. Finally, the playback profiles are shown.

A.2 Background

The ideal tools with which to conduct modern power system research would be custom designed inverters from which the exact currents could be exactly manipulated. These would be no different in basic hardware form from the final commercially available inverter. However, the research time and investment to produce such a system was infeasible at the time of the research.

Since the focus of the research was the control and manipulation of active power, the simulator was created using off-the-shelf variable speed drives. Since energy must be conserved, increasing the mechanical power delivered or absorbed by a variable speed drive will need to originate from the connected power system. These variable speed drives therefore need an initial voltage and power source to bootstrap them, before they can begin to produce power. This was provided by a synchronous machine, which also serves as a voltage and inertial source during operation.

Further these variable speed drives were not designed to operate with an adjustable current profile. Therefore the control and management of their reactive power is predefined by their design.

A.3 Power connections

For the experiments performed in this research the microgrid was wired as though connected to a low impedance busbar. Although plans are in place to incorporate a 'path panel' that can accommodate the creation of different areas and interconnect them via well-defined impedances, this has influence on the work performed.

As such the grid was connected as demonstrated in Figure A.1. Where the isolated microgrid is essentially a low impedance busbar.

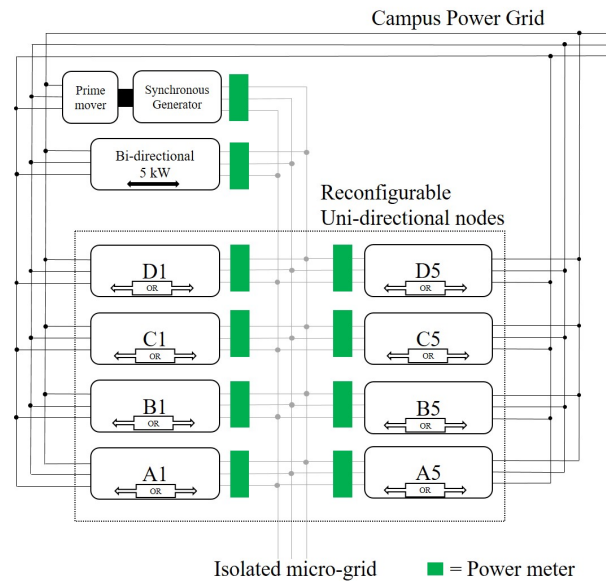


Fig. A.1 Grid Power connections

A.4 Control connections

All controlled nodes on the WPHS are controlled via ModbusTCP over shielded Ethernet cables. This allows for an open-source communication standard to be accessible to a variety of platforms. Where required a protocol translator is used.

The connections to the ModbusTCP devices is then facilitated by IDX Data Exchange server. This handles the cyclic (every 100 ms) communication with the devices and collates all the data into a single read and write accessible database. This is then accessed via OPC.

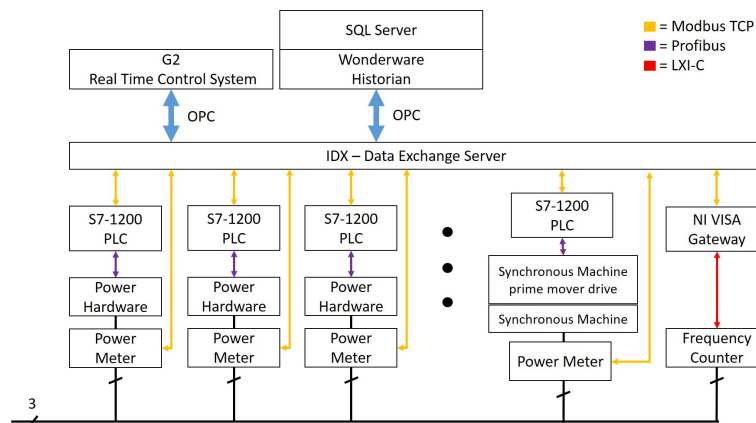


Fig. A.2 Grid communications

Table A.1 Maximum allowable error for power meters with matched current transformers

Measurement	Maximum Error
Voltage	0.1%
Current	0.1%
Real Power	0.3%
Power Factor	0.5%

A.5 Measurement system

The measurement system used to capture and record the power measurements of each node is made up of a power meter (PPMx23) produced by a South African company, Master Power Technologies. The meters have been tested under the IEC62052-11 and IEC62052-22 and verified by independent labs under class 0.5. The meter utilises an Analog Devices ADE7880 Digital power meter at its core. The signals to the ADE7880 are provided via resistive voltage dividers and LEM current sensors (LTSR 6-NP). This chip is interfaced to a PIC32MX795 microcontroller which interfaces with the Ethernet port. The device is capable of fast update rates from the power measurement IC to the Ethernet port. The values on the power meter are accessed via MODBUS TCP. Critical measurements (Currents, frequency power and voltage) are transferred as 32 bit floats. The PIC32 microcontroller does apply a moving average filter to the voltage and total harmonic distortion (THD). There are no delays or timers on the reception of all other available values from the ADE7880 to the modbus cache.

Each power meter was mated to a set of current transformers. These current transformers were purpose designed for this application by Current Electric. All current transformers used are Class 0.1.

A.5.1 Static Calibration

Each power meter was further calibrated with its matching current transformer set. The maximum allowed error is detailed in Table A.1. This was performed at the Master Power Research and Development laboratories. All power meters used in the experiments possess calibration certificates verifying their accuracy with their mated current transformers.

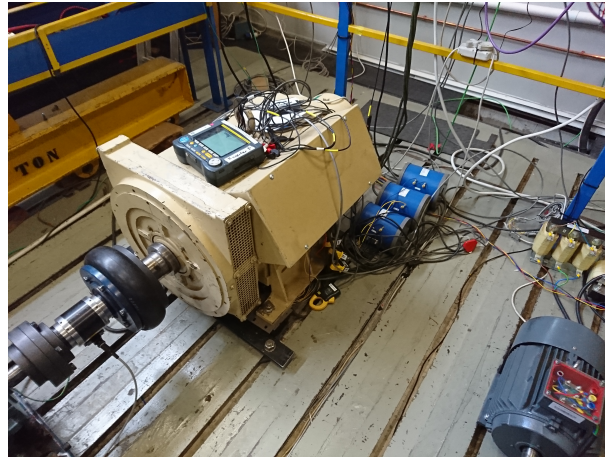


Fig. A.3 Synchronous machine used

A.5.2 Dynamic Performance

The dynamic behaviour of the power meters is primarily dependent on the ADE7880 IC itself. From the datasheet of the ADE7880, it can accurately track frequency changes of up to 10 Hz. The active power is calculated by the Digital Signal Processor (DSP) of the IC at 8 kHz. Therefore, the dynamics of the IC are fast enough for the purposes of the research performed.

A.6 Synchronous Node

The synchronous machine provides both a means of black starting the power system, providing a failsafe power source and provide a variable source of reactive power for regulating the voltage. During the normal operation of the power system, the synchronous node also emulates the behaviour of a variable mass flywheel .

A.6.1 Hardware

The synchronous node is a 90 kV · A Synchronous machine shown in Figure A.3, with a brushless excitation system and integral fan, the nameplate data is given in Table A.2. The machine is driven by a 5,5 kW induction motor (Table A.3) which is controlled via a 5,5 kW four quadrant drive. The drive is operated in closed loop speed control mode with feedback provided via an incremental shaft encoder(5000 pulses/revolution, RS Electronics: 291-4349). The drive controller (Siemens Sinamics CU250-S DP, 6SL3246-0BA22-1PA0) is controlled

Table A.2 Synchronous Machine nameplate data

Manufacturer	Siemens LTD. Lic. Unelec.
Type	AT 250 LB3D
S	72 kV · A
PF	0.8
P	72 kW
RPM	1500
Hz	50
Voltage	400 V
Current	130 A

Table A.3 Prime mover (induction machine) nameplate data for the synchronous machine.

Manufacturer	Siemens
Type	3~ Motor 1LA7130-4AA60-Z
F	50 Hz
PF	0.81
P	5,5 kW
RPM	1455
Voltage	380 V to 420 V
Current	11,4 A to 11,9 A

Table A.4 Nameplate data for the four quadrant drive used.

Type	Sinamics Power Module 250
Product Code	6SL3225-0BE25-5AA1
Input	380 V to 480 V 18,0 A 50/60 Hz
Output	0- input V 18,0 A
Motor	IEC 5,5 kW

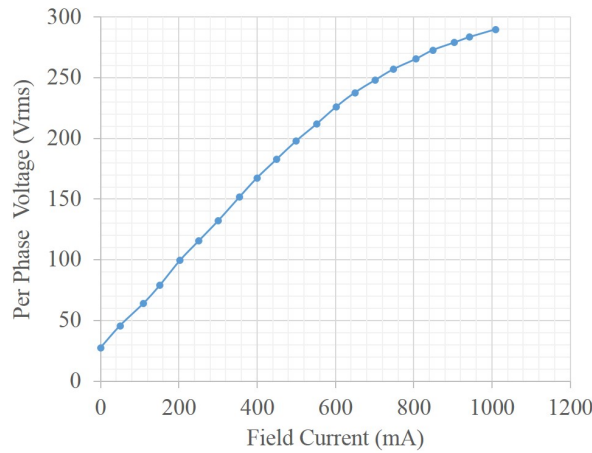


Fig. A.4 Short circuit per phase current vs brushless exciter current at 1500 rpm of synchronous machine used.

by a PLC (Siemens S7-1200 1214C), which is able to communicate with the drive through the Profibus interface (Siemens CM1243-5).

A.6.2 Machine parameter identification

The open and short circuit characteristics of the synchronous machine is presented in Figures A.4 and A.5. Therefore the series impedance is measured to be $4,6 \Omega$ at 50 Hz [76].

A.6.3 Mechanical losses

The synchronous machine consists of a integrated fan and brushless exciter which increases the mechanical loading of the machine. The mechanical losses of the machine was measured in a no load test, the results are shown in Figure A.6.

The synchronous machine was then setup to maintain 1500 rpm as the excitation was varied. The impedance of the exciter was measured to be $18,6 \Omega$. The results of this test is shown in Figure A.7. This shows that increasing the excitation, and hence increasing the reactive power exported by the machine during operation does lead to an increase in the mechanical power required to maintain the desired rotary velocity. This does affect the active/reactive power decoupling assumption of the synchronous element. The effects of the excitation on the mechanical loading will be analysed later in conjunction with the effects of the other grid devices.

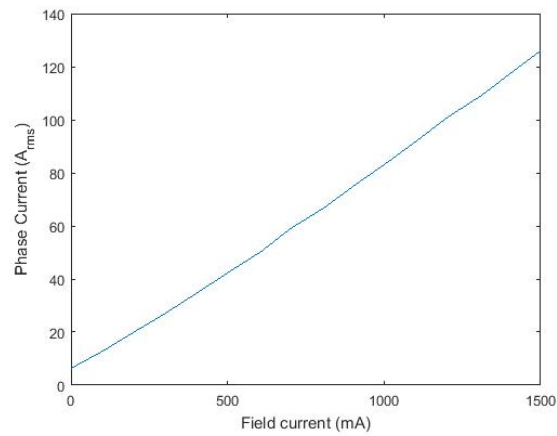


Fig. A.5 Open circuit per phase voltage vs brushless exciter current at 1500 rpm of synchronous machine used.

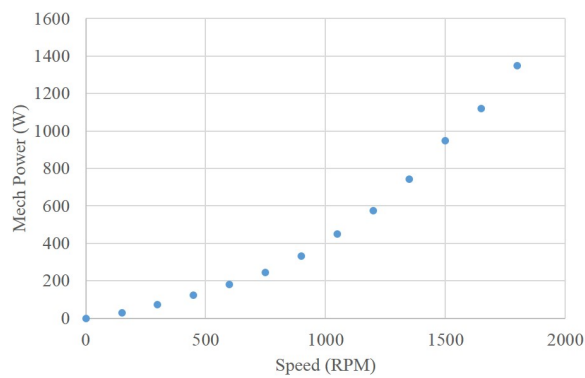


Fig. A.6 Mechanical power required to maintain a specific RPM of the synchronous machine with no excitation.

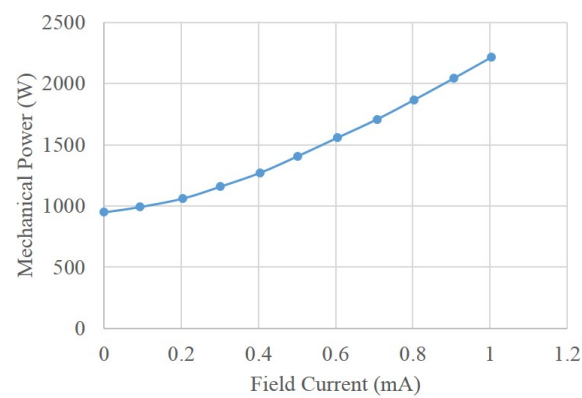


Fig. A.7 Mechanical power required to maintain 1500 rpm vs exciter current of the synchronous machine.

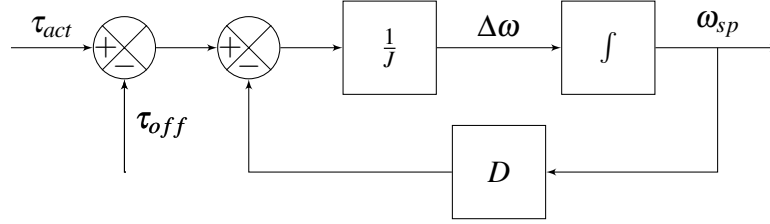


Fig. A.8 Continuous representation of virtual inertia emulation

A.6.4 Virtual inertia

The drive controller provides the PLC with the approximated torque used to maintain a speed setpoint. This is used to approximate the next speed setpoint ($\omega[n+1] = \omega[n] + \Delta\omega$) using Equation A.1, needed to emulate a specific moment of inertia.

$$\tau_{mea} - \tau_{off} = J\Delta\omega + D\omega \quad (\text{A.1})$$

Where τ_{mea} is the torque moment provided by the variable speed drive to maintain the previous speed setpoint. τ_{off} is an constant offset torque, and D is the set droop coefficient. This approximately models the dynamics of the swing equation.

A.6.5 Droop

The torque offset, τ_{off} (Equation A.1), can be manipulated to implement a droop response. This can be used to reduce the mechanical loading of the machine at a desired point. Since this is digitally implemented, it can be set to operate only within a desired frequency range. Alternatively the droop implemented by D can be programmed to operate only in specific ranges.

A.6.6 Dynamic Performance

The synchronous machine has a mechanical moment of inertia of about $0,05 \text{ kg} \cdot \text{m}^2$. During the research the minimum emulated inertia was $1,0 \text{ kg} \cdot \text{m}^2$. Due to inherent delays in the response of the drive to an immediate change in the actual speed of the synchronous machine, there is a non-ideal frequency deviation.

In order to classify the dynamic error of the inertia emulation, the power into the synchronous machine (Figure A.10) was recorded every 5 ms along with the frequency (Fig-

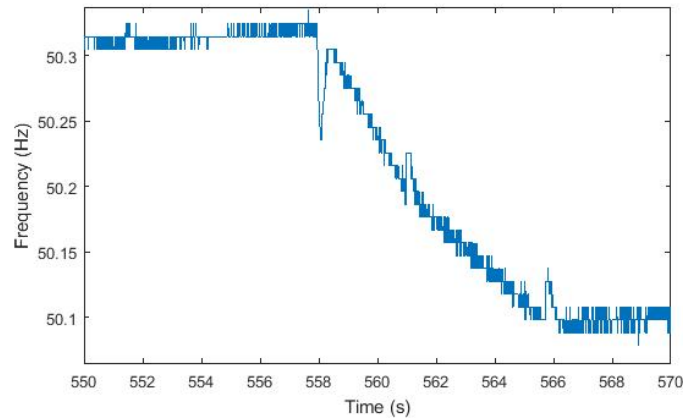


Fig. A.9 Measured frequency of synchronous machine, emulating $50 \text{ kg} \cdot \text{m}^2$ during a disturbance.

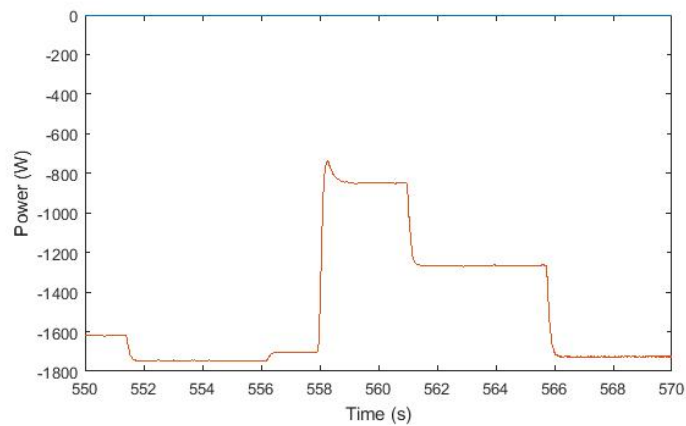


Fig. A.10 Power absorbed by synchronous machine, emulating $50 \text{ kg} \cdot \text{m}^2$ during a disturbance.

Table A.5 Nameplate data for the torque sensor on the synchronous machine .

Manufacturer	Magtrol SA
Type	TMB 212
Rated Torque	200 N · m
Sensitivity	25 mV/(N · m)

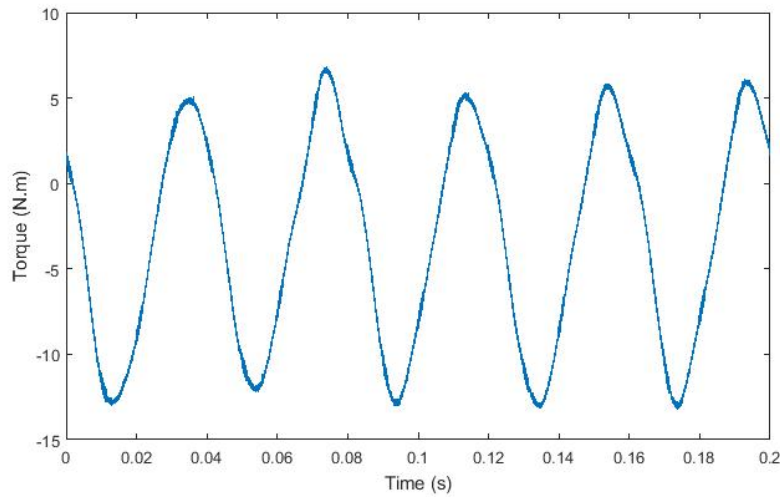


Fig. A.11 Torque supplied to synchronous machine under no load and no applied excitation

ure A.9). The power into the synchronous machine was varied every 5 s. These figures show the non-ideal frequency deviation, which is restored to desired values within 1 s.

Over time the actual frequency error is nominal, due to the limited resolution of the measurement and the integral nature of the inertia emulation.

A.6.7 Torque Noise

To validate experimental results a torque sensor was connected between the prime mover and the synchronous machine. The nameplate data of the sensor is given in Table A.5.

Due to alignment issues with the synchronous node, a slight oscillation is noted in the measurement of the torque. This was verified using a torque transducer. The waveform of the torque measured during no load conditions at 1500 rpm is shown in Figure A.11. Note that during the test the synchronous machine has no electrical load (and no applied excitation). This results in a torque requirement of about 900 W ($\approx 3,4 \text{ N} \cdot \text{m}$ at 1500 rpm).

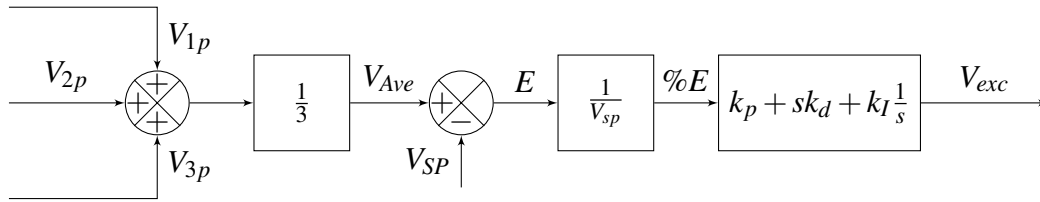


Fig. A.12 Voltage control for the synchronous machine

A.6.8 Voltage regulation

In order to black start the power simulator, the only unit capable of producing a voltage is the synchronous node. Further the synchronous node was the only unit capable of varying its reactive power output. Therefore, the synchronous node is the only node that responds to changes in the voltage. The current out of an analogue output module (0 mA to 20 mA) on the PLC controlling the synchronous node (AQ1 x 12 bits, 6ES7 232-4HA30-0XB0), was amplified to be capable of applying the full voltage to the exciter, V_{exc} (0 V to 16 V).

The control of the excitation was performed by a PID controller implemented on the central computer, detailed in Figure A.12, every 100 ms. First the average phase voltage V_{ave} is calculated from the three phase-neutral voltages, V_{1p} , V_{2p} and V_{3p} . This is compared to the nominal voltage set point V_{SP} , to get the absolute error E , before being divided by the setpoint to get the percentage error. The PID controller function is then applied to the percentage error to get the excitation voltage setpoint, V_{exc} . The gains for the PID controller were set to $k_p = 10$, $k_I = 40$, $k_d = 1.5$.

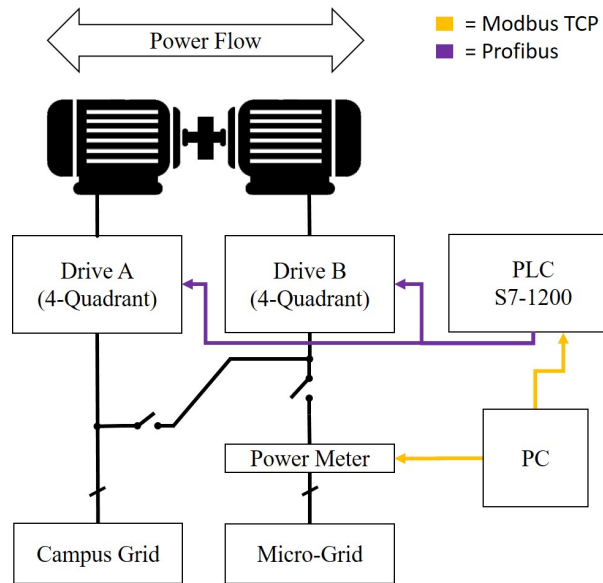


Fig. A.13 Bidirectional node wiring

Table A.6 Nameplate data for bidirectional node machines in delta configuration.

Manufacturer	Actom Electrical Machines ZA
Type	3~ Motor LS5130-4AH 132S
P	5,5 kW
V	400 V
A	11,5 A
Hz	50 Hz
PF	0.79
Speed	1460 rpm

A.7 Bidirectional node

The bidirectional node consists of two 4 quadrant drives (as detailed in Table A.4) driving two induction machines (Table A.6) that are mechanically coupled. Feedback is provided to both variable speed drives from an incremental shaft encoder (5000 pulses/revolution, RS Electronics: 291-4349). Both drives are controlled with a CU250-S drive controller (Siemens Sinamics CU250-S DP, 6SL3246-0BA22-1PA0) the setpoints for both drives is set from a single PLC (Siemens S7-1200 AC/DC/Rly).

Drive A operates the machine via a closed-loop torque control mode. Drive B is operated in closed loop constant speed mode.

Table A.7 Nameplate data for the two quadrant drive used.

Type	Sinamics Power Module 240
Product Code	6SL3224-0BE22-2AA0
Input	380 V to 480 V 7,6 A 50/60 Hz
Output	0-input V 5,9 A
Motor	IEC 2,2 kW

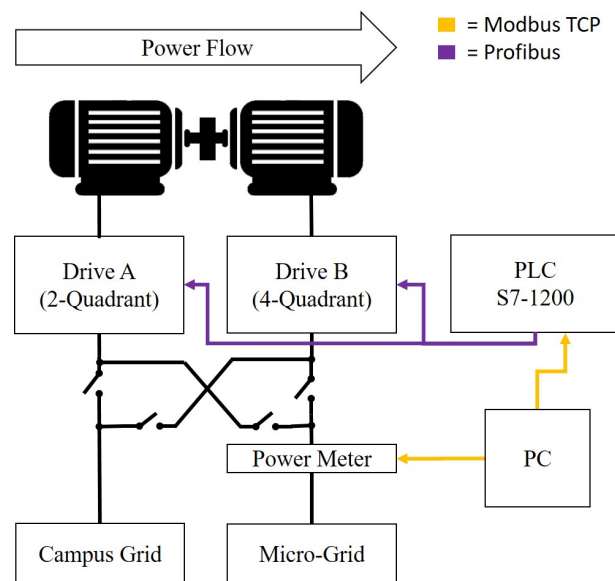


Fig. A.14 Unidirectional node wiring

A.8 Uni-directional node

The unidirectional node consists of two induction machines that are mechanically coupled illustrated in Figure A.14. One of the machines is driven by a PM 250 (Table A.4), the other is driven by a PM 240 power module (Table A.4). Both power modules are controlled with a CU250-S drive controller (Siemens Sinamics CU250-S DP, 6SL3246-0BA22-1PA0) the setpoints for both drives is set from a single PLC (Siemens S7-1200 AC/DC/Rly). Speed feedback is provided to both drives from an incremental shaft encoder (5000 pulses/revolution, RS Electronics: 291-4349).

The node is configured such that it can be operated as a power source or sink for the microgrid. This is achieved via the contactors, which are controlled by the PLC. By means of example the node can be configured as a power source by closing the contactors as shown in Figure A.15.

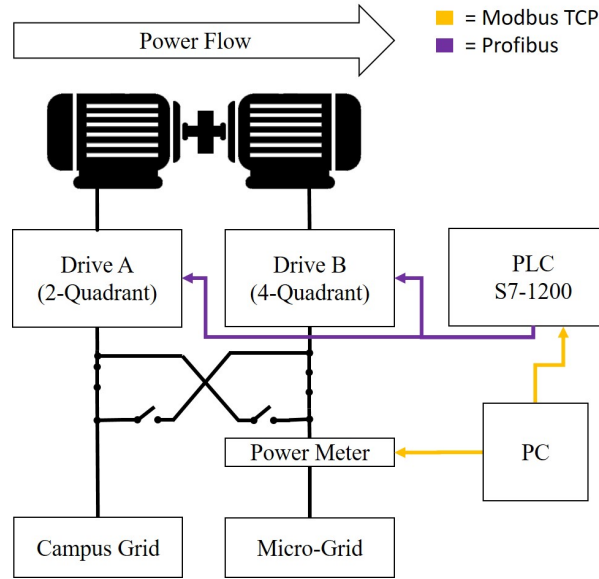


Fig. A.15 Unidirectional node wiring when operating as a power source

A.9 Resulting Dynamic Error

In order to account for the error that occurs due to the delays in response of a responsive node, it is imperative to examine the way in which this error manifests. The main difference between the mathematical and software models of the system is the energy that physically reaches the inertial element. Since the hardware emulator utilised a discrete time control, the energy transmitted from a node during the controller delay needs to be considered. Ideally the energy E_{T_n} from a node during a discrete time period T with power $P(T_n)$ should be

$$E_{T_n} = \int P(T) dt = P(T_n) * T \quad (\text{A.2})$$

However in the case of the actual devices used in the experiments there is a derating in terms of the actual energy output during a control cycle, due to the rise and fall times of the output from the inverter.

This derating is determined by applying step changes to the power setpoints and measuring the actual power coming out of the node. The energy actually output by the machine is then compared to the ideal energy that should have been transferred.

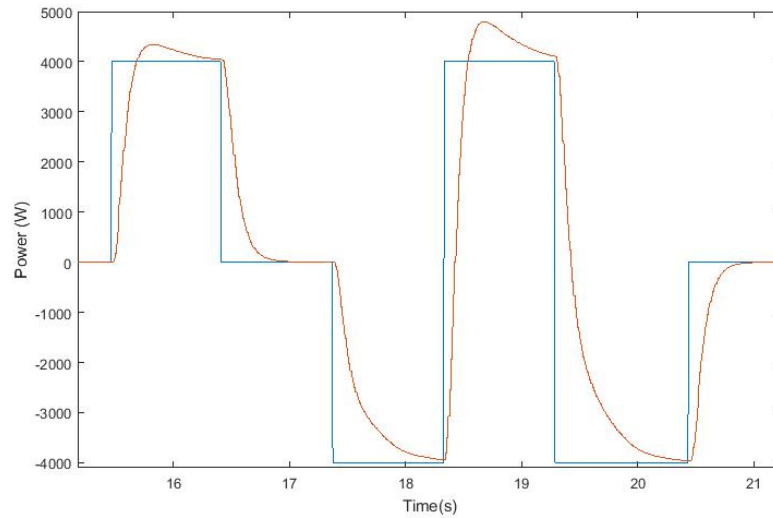


Fig. A.16 Actual power out (red) vs power setpoint (blue), for all permutations of transitions between 4 kW, −4 kW and 0 kW for the bidirectional node.

Table A.8 Measured differences in energy for all permutations of transitions between 4 kW, −4 kW and 0 kW for the bidirectional node. Average error of 24.0 %

Original Setpoint	Setpoint	Ideal Energy (W·s)	Actual Energy (W·s)	Error (%)
0 kW	−4 kW	-3840	2967.9	22.7
0 kW	4 kW	3840	2984.2	22.3
4 kW	−4 kW	-4600	-2897.2	37.0
−4 kW	4 kW	3820	3285.4	14.0
4 kW	0 kW	0	564.6	
−4 kW	0 kW	0	-535.4	

A.9.1 Bidirectional node

The bidirectional node was controlled to a set of step changes to cover all possible permutations of −4 kW, 0 kW and 4 kW with 1 second in between changes. The actual power output is plotted in Figure A.16.

Each region of interest was integrated with the energy ideally sent compared to the energy actually accumulated. This is outlined in Table A.8. This was then repeated for smaller setpoint changes of 1 kW as shown in Figure A.17. The results of this test is summated in Table A.9.

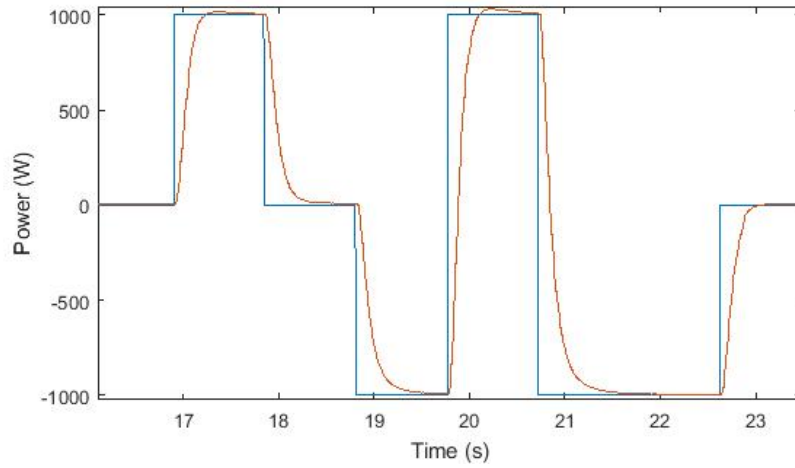


Fig. A.17 Actual power out (red) vs power setpoint (blue), for all permutations of transitions between 1 kW, -1 kW and 0 kW for the bidirectional node.

Table A.9 Measured differences in energy for all permutations of transitions between 1 kW, -1 kW and 0 kW for the bidirectional node. Average error of 19.7 %

Original Setpoint	Setpoint	Ideal Energy (W·s)	Actual Energy (W·s)	Error (%)
0 kW	-1 kW	-965	799.23	22.7
0 kW	1 kW	965	839.9	13.0
1 kW	-1 kW	-1905	-1580.6	17.0
-1 kW	1 kW	950	713.33	24.9
1 kW	0 kW	0	149.2	
-1 kW	0 kW	0	-129.6	

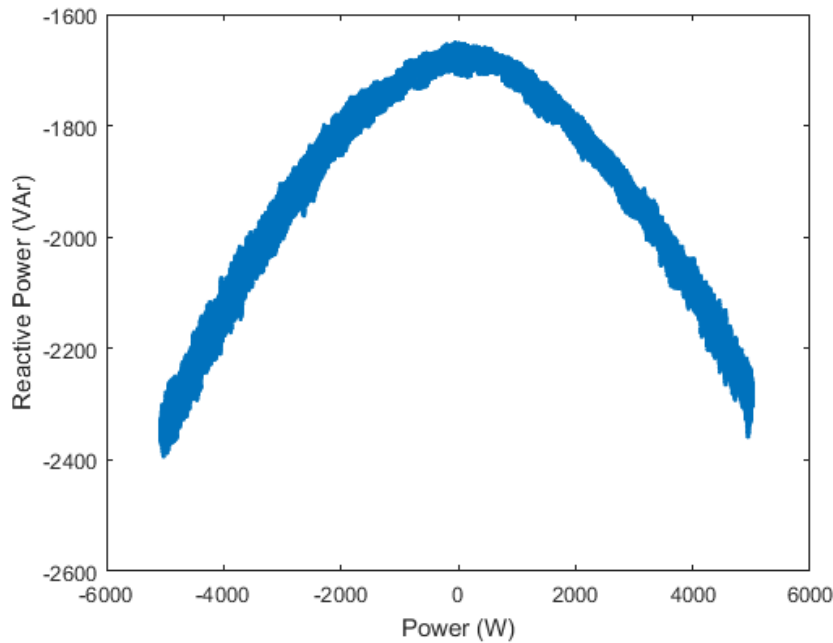


Fig. A.18 Reactive power as a function of Active power for the bidirectional node

Reactive Power

The node was controlled to perform a sweep of the range of output setpoints available. The reactive power was logged and is plotted as a function of active power in Figure A.18.

Since the reactive power is not controlled during the simulation, this reactive power requirement is independently managed by the variable speed drive (the PM 250). While there is a correlation between the active and reactive power, it is fairly small, $\approx 0,15 \text{ var/W}$ resulting in a negligible change in the excitation when powered from the synchronous machine.

A.9.2 Unidirectional node

While the node was configured as both a power source and sink it was sent to its 2 kW power setpoint extremes (Figures A.19 and A.20). The results are summed up in Table A.10.

Reactive Power

The reactive power component of the unidirectional node as a load is significantly affected by the active power setpoint as shown in Figure A.21. This is largely due to the differences in the

Table A.10 Measured differences in energy for all permutations of transitions between -2 kW , 2 kW and 0 kW for the unidirectional node.

Original Setpoint	Setpoint	Ideal Energy (W·s)	Actual Energy (W·s)	Error (%)
0 kW	-2 kW	-3780	3639.3	3.7
0 kW	2 kW	3720	3640.7	2.13
2 kW	0 kW	0	256.0	
-2 kW	0 kW	0	-262.7	

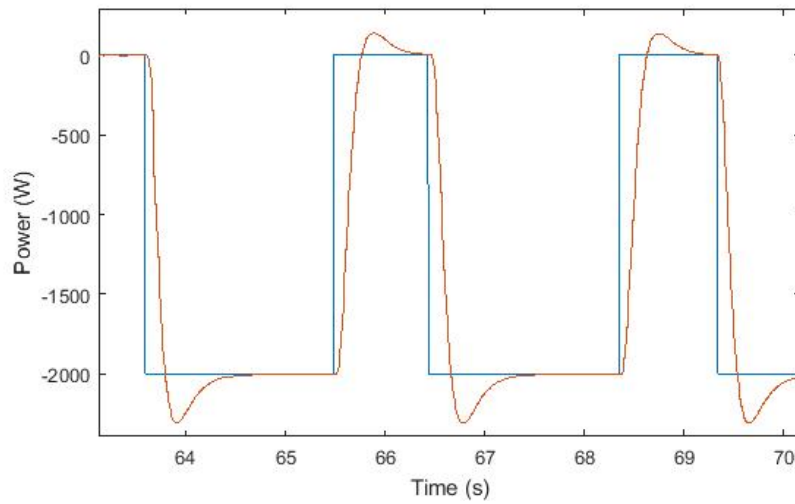


Fig. A.19 Actual power (red) vs power setpoint (blue), for the unidirectional node as a power source for 2 kW setpoint step changes.

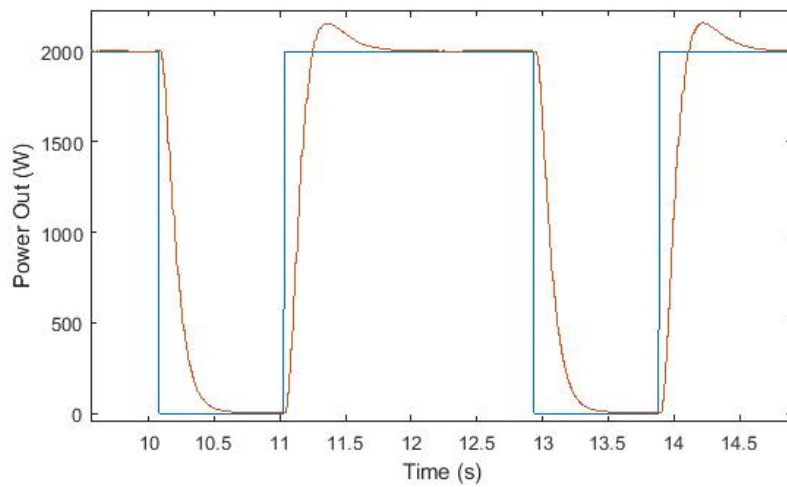


Fig. A.20 Actual power (red) vs power setpoint (blue), for the unidirectional node as a power sink for 2 kW setpoint step changes.

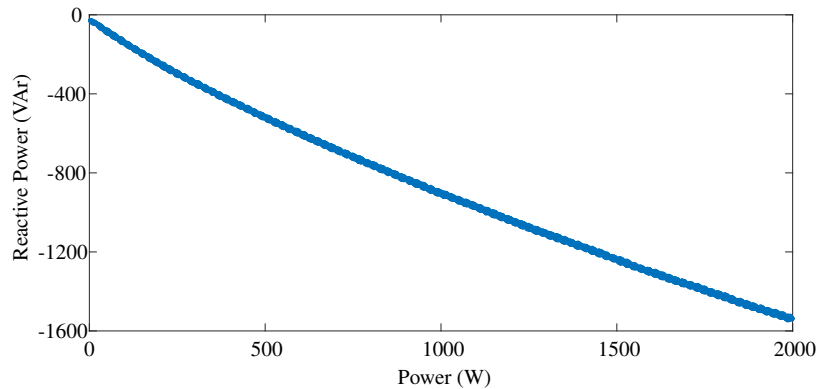


Fig. A.21 Reactive power as a function of Active power for the unidirectional node as a load

input stage of the two quadrant PM240 as opposed to the four quadrant PM250. Linearising the Figure A.21 gives an approximate relationship of 0,8 var/W.

The node was then powered by the synchronous node. The results of applying a 0 kW to 2 kW load as shown resulted in an excitation setpoint of the synchronous machine to increase from 11,76 V, to 12,08 V respectively to maintain the nominal phase voltage (240 V). This meant an approximate increase of mechanical power drawn, due to the brushless exciter of 30 W (extrapolating Figure A.7). During the experiment, a difference of around 120 W was noted from the torque sensor. It should be noted that the torque sensor sensitivity (Table A.5) might contribute to errors in detecting this difference in torque (1 N · m at 1500 rpm is approximately 157 W).

Therefore, the additional effect on the real power of this node, due to the reactive power component is 15 mW/W to 75 mW/W.

A.9.3 Harmonic noise

The drives used as power hardware interfaces used in this setup are off the shelf variable speed drive solutions and not intended for this purpose. As such they do not take care in filtering their outputs. It should be noted that both the PM240 and PM 250 interface to the grid via input chokes (Siemens Code: 6SL3203-0CD21-0AA0 and 6SL3202-0AJ23-2CA0 respectively). The PM 250 at 5 kW produced approximately 90 % total harmonic distortion on the current. The PM 240 produced a THD of 74 % at 2 kW. Example waveforms of the voltages and currents when operating a single unit alone, is shown in Figure A.22.

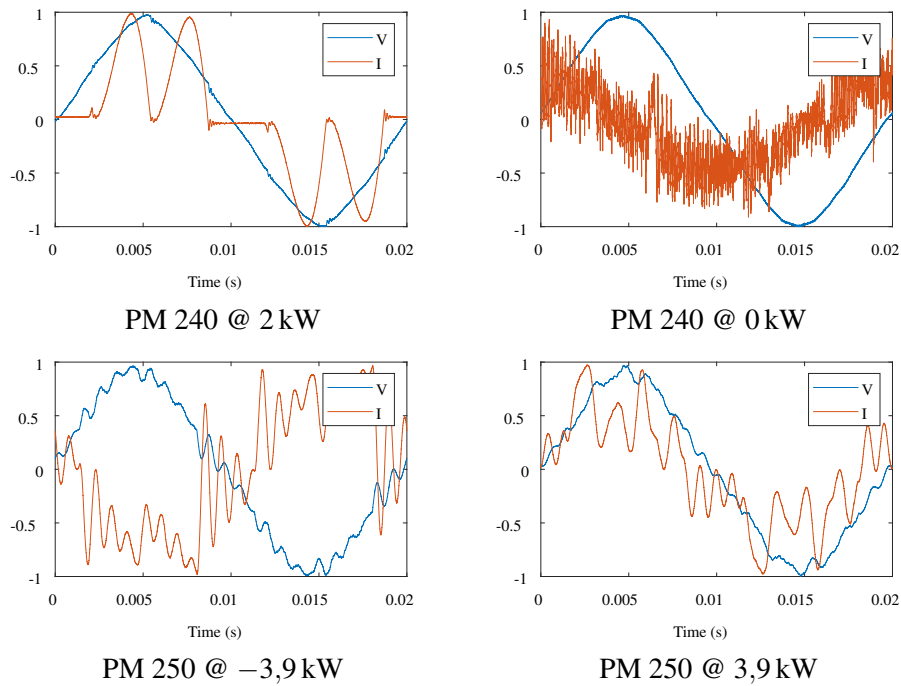


Fig. A.22 Examples of normalised phase voltages and currents for PM240 and PM250 drive units measured at their grid-side power meter (Figure A.13, Figure A.14)

A.9.4 Analysis

It can be reasonably assumed that these errors carry through to the experiments conducted. The energy error from these tests are always less than the ideal energy (even with the offshoot). The magnitude of the error is dependant on the direction of the transition (ie, more generation vs more load), hence difficult to model. The unidirectional node, shows the lowest error, whereas the bidirectional node demonstrates larger errors for larger energy swings.

In the experiments performed, the unidirectional nodes provided fixed setpoints of power to mimic solar generation or a known load profile. Hence, they do not greatly affect the accuracy of the experiments. The bidirectional node implements the dynamic loading or generation. In these experiments, the node implements a fixed gain. Under unstable conditions the setpoint implemented by this node increases to large swings. As has been shown by Tables A.8 and A.9, from an average error of 20 % to 24.0 % as the swing increases from 1 kW to 4 kW the error of the node increases as the swing between setpoints increases. Therefore as the system became more and more unstable, the effective gain of the bidirectional node decreases.

Therefore the demonstration of intentionally unstable conditions has an error of at least 25 % in the effective gain of the responsive node.

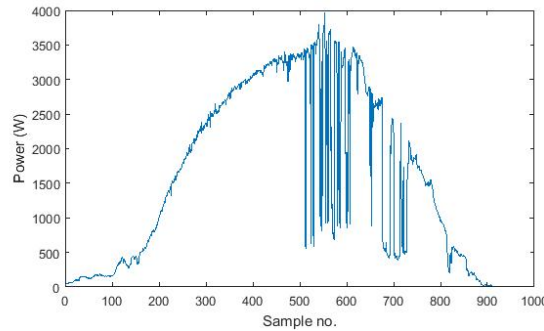


Fig. A.23 Solar1 profile: actual power recorded from Terence Eden on the 10th of July 2014.

A.10 Playback Profiles

In order to emulate the behaviour of certain loads and sources, the power samples from actual systems were captured and reproduced. Before playback these profiles are scaled to ensure the peak playback values are still below the maximum output of the node emulating the profile.

A.10.1 Solar Profiles

The data used for the solar profiles is minute by minute samples freely available from Terence Eden's Blog [152]. These contain the power consumption of his personal solar system, for which he has recorded data for a year. Specific days were chosen for certain characteristics.

Solar1

Chosen for its nominal morning, and slightly cloudy mid-afternoon, this profile was recorded on the 10th of July 2014.

Solar2

Chosen for its very stochastic cloud cover the whole day, this profile was recorded on the 19th of June 2014.

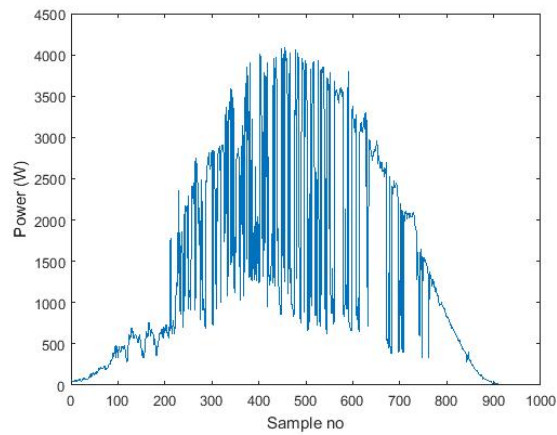


Fig. A.24 Solar2 profile: actual power recorded from Terence Eden on the 19th of June 2014.

A.10.2 Standard Load profile

The load profile is an arbitrary load profile observed for an office block. This was recorded on the 21st of May 2015.

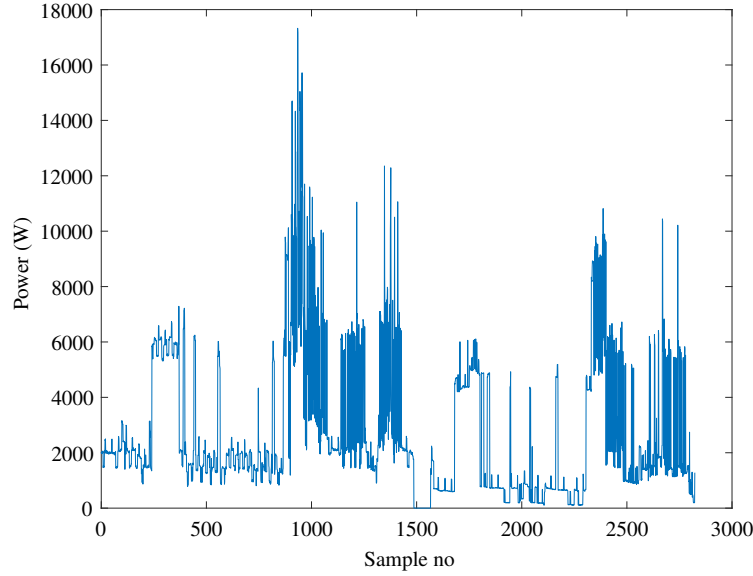


Fig. A.25 Active power samples for a business recorded 21st of May 2015.

A.11 Practical considerations

The nature of the components used in the power hardware-in-loop setup (specifically the variable speed drives, Tables A.4 and A.7, means that in order to continually run the experiments, the voltage and frequency need to be kept above 380 V and 45 Hz respectively. If the grid parameters drop below these values, the variable speed drives will need to be restarted, a process which takes about 15 to 30 seconds.

In order to avoid going into this condition, a frequency limit f_{lim} is set before the start of the experiment. The experiment should be designed to avoid going below this limit. Due to the inherent 1,7 kW to 2,0 kW load presented by the synchronous machine, a low frequency droop (τ_{off} in Figure A.8) is incorporated in the control of the synchronous node as described.

$$\tau_{off} = \begin{cases} 0, & f_{grid} \geq f_{lim} \\ k \left(\frac{f_{grid} - f_{lim}}{f_{dev}} \right) & f_{grid} < f_{lim} \end{cases} \quad (A.3)$$

Where f_{dev} is the allowed frequency deviation from f_{lim} (often 1 Hz) and k is such that the synchronous machine presents no electrical load to the system at $f_{lim} - f_{dev}$. This only impacts the low frequency operation of the system.

When this limit is reached during experimentation, the simulated system is essentially in a black start or blackout condition. This cannot be further investigated on the system due to the Siemens Inverters requiring about 30 seconds after sufficient voltage has been reached before they can be used.

A.12 Conclusion

While software simulation goes a long way towards the verification of new grid control theorems and algorithms, it is inherently an idealised system. The complete commissioning and testing of an actual power system is expensive and difficult to modify. Using power-hardware-in-loop simulators allows for the flexible and reproducible testing of new algorithms and theories, with the inclusion of non-ideal effects of an actual operation. The power-hardware-in-loop simulator presented herein allows for the grid control theorems to be tested in the presence of delays and noise present in actual systems.

Due to the fact that the components used in this research were off the shelf components not intended for this purpose, certain non-ideal effects were analysed and characterised. These non-ideal phenomena will affect the accuracy of the simulations performed.