

An Interface for a Photovoltaic Module to an Ad-hoc, Low Voltage, DC Distributed Grid

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Mohammed Raees Ebrahim Dangor
Johannesburg, May 2019

I dedicate this research to those who would benefit from it. . .

Abstract

This research has contributed to the advancement of the Personal Consumer (PeCo) grid concept and has furthered the technology from a conceptual prototype to becoming a viable rural electrification solution. The PeCo grid is a conceptual ad-hoc, 12V, DC distributed grid aimed at providing an electrification solution for single rural households. The grid is composed of an interconnection of renewable energy sources, battery storage and loads. A shortcoming of the PeCo grid, exposed on the first experimental prototype grid, was that undesirable over-voltages occurred during load removal events due to an over-supply of power to the grid after the load was disconnected. This research entails the development of an interface for a photovoltaic (PV) module to the PeCo grid that aims to overcome this shortcoming and to extend the capabilities of and further the technology. At the interface, the voltage of the PV module is matched to the grid voltage. Power flow from the PV module to the grid is controlled according to a control strategy modelled as a state diagram and executed by a micro controller unit (MCU). The power converter at the interface is a Flyback converter operating in discontinuous conduction mode (DCM). A model was derived to estimate the primary-side inductor current of a DCM Flyback converter and applied to perform model-based maximum power point tracking (MPPT). This obviated the need for any current sensors at the interface. The response of the MCU to a load removal event was tested and validated to overcome the shortcoming of the experimental grid. The model-based MPPT solution was tested using the PeCo grid as a test platform and validated to successfully perform MPPT. The real world application of the interface was validated and the technology deemed suitable for rural electrification.

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Nomenclature

Acronyms / Abbreviations

AWG	American Wire Gauge
CC	Current Control
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction mode
ES	Energy Storage
GEN	Generation
IC	Integrated Circuit
MCU	Micro Controller Unit
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
OP	Operating Point
PeCo	Personal Consumer
PFM	Pulse Frequency Modulation
PLC	Programmable Logic Controller
PV	Photovoltaic
PWM	Pulse Width Modulation

RES Renewable Energy Source

SMPS Switch Mode Power Supply

VC Voltage Control

Chapter 1

Introduction

Distributed generation is an energy generation paradigm based on the localised generation, consumption and possible storage of energy. Energy is generated from renewable energy sources (RES) such as wind or photovoltaic (PV) and stored in batteries which are components of an energy storage (ES) system. An interconnection of RES elements, ES systems and loads form a distributed grid. The Personal Consumer Grid or PeCo grid is a standalone, ad-hoc, 12V, DC distributed grid. The PeCo grid is an endeavour to provide a low-cost, plug-and-play scalable, autonomously operating, robust electrification solution for single rural households. The PeCo grid is composed of an interconnection of blocks, as in building blocks. There are 3 variants: a generation (GEN) block, an ES block, and a Load block. Each block is composed of their respective RES, battery or load element and an interface. A rudimentary architecture of the PeCo grid is illustrated by Figure 1.1. At each interface, there is a DC-DC power converter and a control platform which executes a control strategy to control power flow between the element and the grid. The aim of the control strategy is to keep the grid voltage within a stable region bounded by a minimum and maximum voltage. This is achieved by constantly approaching a fixed nominal voltage within the bounded range. The grid voltage does not settle, but rather fluctuates about the nominal voltage. Voltage spikes or dips out of the stable region are undesirable. Operation above the stable region indicates an oversupply of power to the grid and operating below the stable region indicates an undersupply of power to the grid.

1.1 Research Problems

1.1.1 Interfacing a PV Source

The PeCo grid concept has been validated on a grid composed of prototype blocks built by veterans of this research project [1, 2]. This was the first experimental prototype of the PeCo grid that was built. For the purpose of disambiguation, the first experimental prototype PeCo grid is termed the **Legacy Grid**. DC power supplies were interfaced to the Legacy Grid as sources under controlled conditions. Actual PV, wind or battery elements were not interfaced to the Legacy Grid. It has yet to be validated if these elements can be interfaced to and operate under the context of the PeCo grid.

1.1.2 Load Removal on the Legacy Grid

A shortcoming of the Legacy Grid was that the control platform failed to accomplish the primary control objective during load removal events. For the purpose of disambiguation, a load removal event is defined as any occurrence of there being a disconnection of a load from the grid whether it be accidental or planned. The Legacy Grid operated within the stable voltage region bounded by a minimum voltage of 10 V and a maximum voltage of 14 V. The control aimed to approach a nominal voltage of 12 V to ensure the grid voltage remained within the stable region. Figure 1.2 depicts the response of the grid voltage and load current to a load removal event on the Legacy Grid. At the instant that the load is removed, the load current steps down from 1 A to 0 A. The grid voltage increases and peaks at 18 V. This drastic and sustained increase in grid voltage is undesirable and was the failure of the control platform.

The control platform is supposed to sense the increase in grid voltage above the stable region and respond by curtailing the power supply to the grid. The response of the control platform to sense the voltage increase and to curtail power was not fast enough. There was thus an oversupply to the grid after the load removal. This excess power takes time to dissipate which is represented by the sustained over-voltage during the time $t_{over} = 0.3$ s annotated on Figure 1.2. The time taken for the grid voltage to settle after the load removal was $t_{settle} = 2.04$ s. It was recommended by [2] that the response to a load removal event could be improved by executing the control strategy on a control platform that processes faster than the one used for the Legacy Grid. The

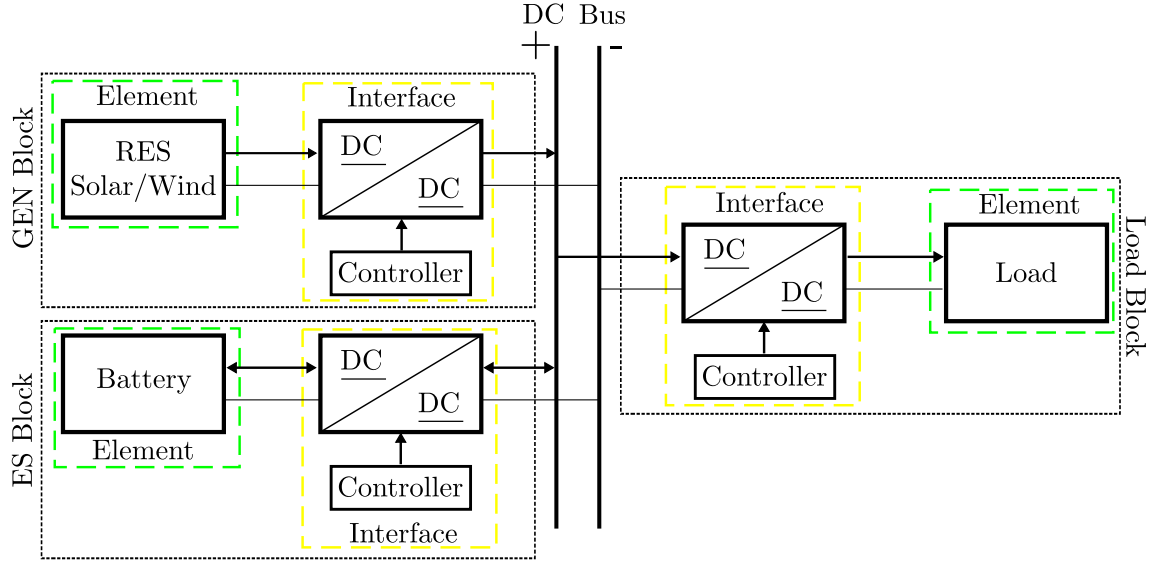


Fig. 1.1 Rudimentary architecture of the PeCo grid.

response is considered improved if the settling time of the grid voltage after a load removal event is faster and if the magnitude of the increase in grid voltage when the load is removed, does not rise above the stable region for a sustained time duration.

1.1.3 Current Sensing in PV Systems

The maximum power point (MPP) of a PV module varies with the availability of solar irradiance and changes in temperature. Maximum power point tracking (MPPT) extracts maximum power from PV modules under varying operating conditions. MPPT is accomplished by means of a MPPT algorithm. The basic premise for most MPPT algorithms is to sense the PV module current and voltage and estimate the power. From this, the algorithm varies the system parameters to track the MPP. The conventional current sensing technique is to use a sense resistor. The major drawback to using a sense resistor is the power loss. Other techniques that aim to overcome this are termed loss-less. A drawback of using loss-less techniques, are that they require current sensors and additional circuitry that is more costly than a single sense resistor. A model-based technique estimates the current using a mathematical model. A model-based technique obviates the need for a current sensor and model-based MPPT can be performed. An accurate model-based MPPT solution can overcome the power loss of the sense resistor technique and the cost drawback of other techniques.

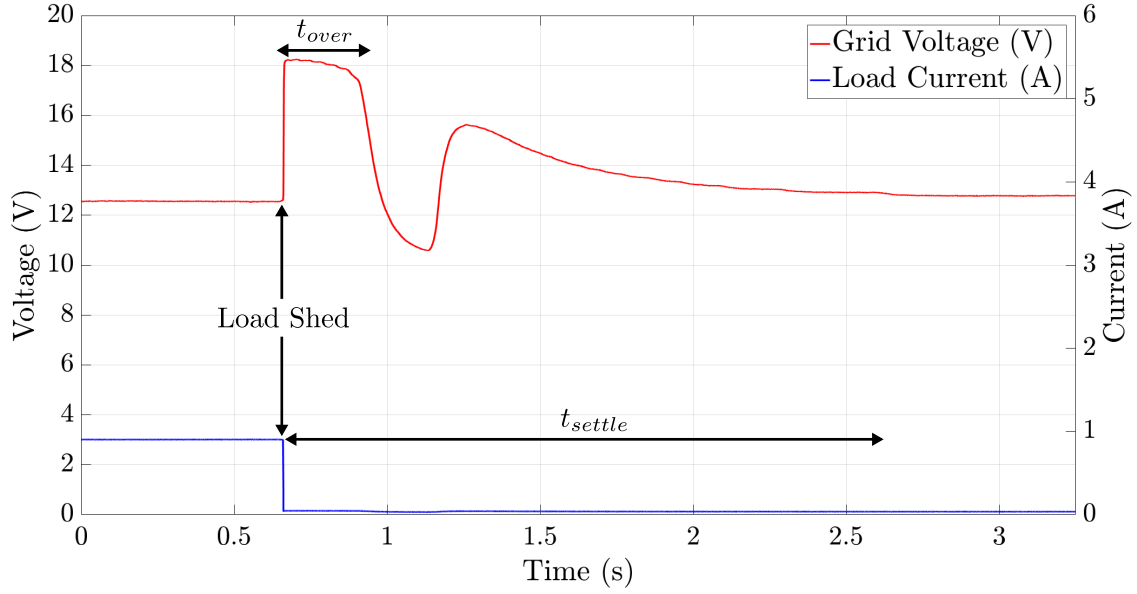


Fig. 1.2 Load removal event on the Legacy Grid.

1.2 Research Aim

The aim of the research presented in this dissertation is threefold and each aim addresses one of the research problems. The aims of this research are:

1. To develop an interface for a PV module to the PeCo grid and validate that a PV module can operate under the context of the PeCo grid.
2. To overcome the shortcoming of the Legacy Grid by revising the control strategy and adapting it to be executed on a control platform that processes faster than the one used for the Legacy Grid.
3. To derive a mathematical model to estimate the PV module current and perform model-based MPPT.

In totality, by achieving each of the aims, the Legacy Grid technology will be advanced and the capabilities extended. This will further the PeCo grid concept to achieving the ultimate goal of providing an electrification solution for single rural households.

1.3 Research Questions

The following research question was formulated:

"What technological advancements can be made to the Legacy Grid to further the PeCo grid from a conceptual prototype to a viable rural electrification solution?"

The following research sub-questions were formulated:

"What technology from the Legacy Grid can be adopted for interfacing a PV module to the PeCo grid and what are the required adaptations to the technology for this purpose?"

"How will a control platform that responds faster than the Legacy Grid control platform respond to a load removal event and will the response be improved?"

"How can the PeCo grid be used as a platform to formulate a model-based MPPT solution for a PV system?"

1.4 Research Objectives and Scope

The first objective of this research was to review existing distributed grid solutions, distributed grid technologies and the Legacy Grid. The scope of this objective was limited to analysing the technology (hardware and software) of the prototype blocks built for the Legacy Grid. Analyses provided a comprehensive insight into the existing technology at the interface.

The second objective of this research was to ascertain what hardware technology is required to interface a PV module to the PeCo grid. The scope of this objective entailed determining what hardware from the Legacy Grid could be adopted and what hardware needed to be adapted to accomplish this.

The third objective of this research was to find a control platform solution that processes faster than the Legacy Grid control platform. The scope of this objective entailed developing of the hardware at the interface to cater for the new control platform.

The fourth objective of this research was to derive a mathematical model that could be used to estimate the PV module current to perform model-based MPPT. The scope of this objective was to derive the model and establish the accuracy of the model.

The fifth objective of this research was to revise the control strategy and execute it on the new control platform at the interface of the PV module to the PeCo grid. The scope entailed adapting and the control strategy for execution on the new control platform and establishing the control response to events on the grid.

The sixth objective of this research was to apply the mathematical model derived from the third objective to perform model-based MPPT. The scope of this objective entailed validating that the model-based MPPT can track successfully track a MPP.

The seventh objective of this research was to interface a PV module to validate the real world application of the interface. The scope of this objective was limited to validating that a PV module can be successfully interfaced to and operated under the context of the PeCo grid. This final objective was set to consolidate the entirety of this research.

1.5 Dissertation Organisation

This dissertation is organised in such a manner as to address the research objectives in the order which they are presented.

Chapter 2 provides the background knowledge for this dissertation:

- A background on the energy crisis that rural regions of the world currently faces is given.
- Distributed grids are reviewed.
- The PeCo grid concept, Legacy Grid and prototype blocks are reviewed.

Chapter 3 the development of the hardware at the interface is presented.

- The prototype block hardware is reviewed.
- The new control platform solution is introduced.
- The hardware is developed to cater for the new control platform.
- Tests conducted to evaluate the hardware and the results are presented with a discussion.

In Chapter 4 the mathematical model for the model-based MPPT solution is derived.

- A background on current sensing techniques and their applications is given.
- The mathematical model is derived.
- Tests conducted to establish the accuracy of the model and the results are presented with a discussion.

In Chapter 5 the control strategy to be executed on the new control platform is developed.

- The goals of the control strategy are presented.
- A background on finite state machine concepts is given.
- The control strategy is modelled as a state diagram.
- Tests conducted to evaluate the control strategy and the results are presented with a discussion.
- The response of the control platform to a load removal event is compared to the response of the Legacy Grid control platform.

In Chapter 6 the model-based MPPT solution is presented.

- A background on PV systems and MPPT algorithms is given.
- Tests conducted to validate the model-based MPPT and the results are presented with a discussion.
- A PV module is interfaced to a PeCo grid to charge a battery interfaced to the grid.

Chapter 7 summarises the findings of this research, answers the main research question and consolidates the recommendations for future research made throughout the document.

Chapter 2

Background

2.1 The Energy Poverty Crisis

The year is 2019 and there are vast rural regions of the world that are in a state of severe energy poverty. These regions are not serviced by an electrical utility-grid and there are 1.1 billion people which accounts for approximately 16% of the human race that rely primarily on the use of burning biomass for their energy production [3–6]. An estimated 95% of these people live in the rural areas of countries in sub-Saharan Africa and developing Asia. These regions in Africa lack any infrastructure for a utility-grid nor do they have the financial means to begin developing one. This makes Africa one of the least electrified continents in the world.

On the contrary, the majority of electrified regions of the world are dominated by centralised generation. This is a century-old paradigm of large-scale power generation from fossil, hydro or nuclear sources at power stations located in regions remote to the eventual region of use. A transmission network is built to transmit power over a great distance from the point of generation to the eventual point of distribution. Centralised generation has a high power capability but requires a large capital contribution, interminable construction and maintenance and the use of fossil fuel sources is hazardous to the environment. Furthermore, finite and diminishing quantities of fossil fuels have resulted in a constant rise in the cost of fossil fuel based energy. Based on these drawbacks, it is improbable that a centralised generation solution can alleviate the energy poverty issue in rural regions.

There has thus been a rise of interest in standalone, low voltage, DC distributed grids. These distributed grids are based on the distributed generation paradigm whereby power is generated from a RES at the point of use and can be stored in ES systems. The use of DC is attractive as it avoids the complexities of AC such as reactive power flow. The idea of DC is further strengthened by the rise in DC appliances and power systems as discussed by [7] and [8] and catalogued in [9]. Due to the lack of a transmission network and the use of RES, a distributed generation solution requires less start-up capital than a centralised generation solution. Distributed grids can be rapidly deployed because there is no need to construct a power station and a transmission network. Furthermore, the lack of an existing power generation infrastructure in rural regions means distributed generation technologies can be introduced at a fundamental level and lead the way for a paradigm shift from centralised generation to distributed generation. The use of RES addresses the concern of there being limited quantities of fossil fuels and the environmental hazards brought upon by their use. There has also been a rise in popularity of solar photovoltaic (PV) technology which has resulted in a decrease in cost and increase in reliability of PV systems. Distributed generation is thus a more pragmatic solution for rural electrification.

To effectively engineer a distributed grid for rural electrification, the electricity requirements of the people in the rural regions are identified. The Energy Sector Management Assistance Program (ESMAP) Multi-tier Framework defines several tiers of electricity access for households [10]. Tiers are quantified by rated power and energy deliverance, see Figure 2.1. Rural communities require up to a tier 2 level of energy usage and the minimum required capabilities of an electrification solution are:

- A power deliverance of 200 Wh/day or 50 W peak power.
- Electricity availability for 4 hrs/day and 2 hrs/night.
- Lighting.
- Cell phone charging.

Extended capabilities would include using electricity for entertainment (television), refrigeration and heating for cooking.

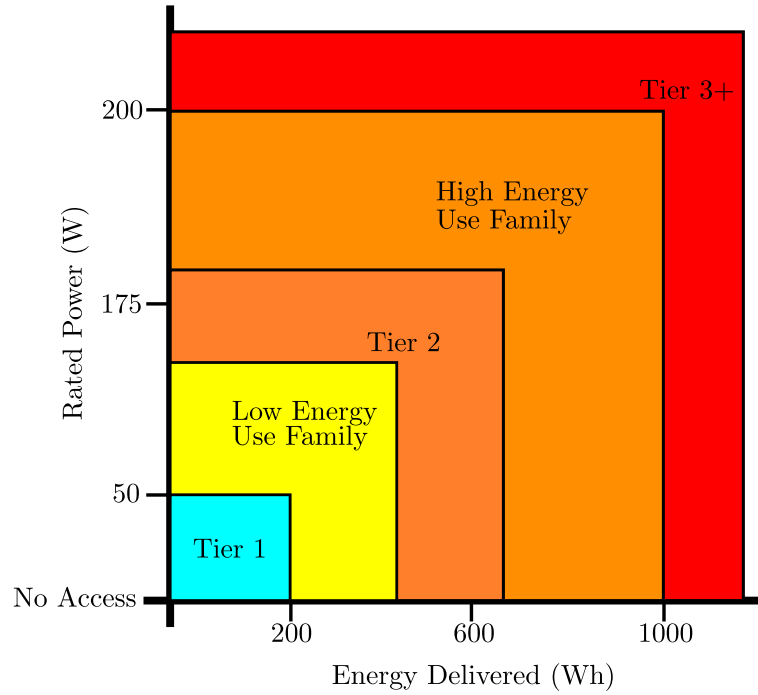


Fig. 2.1 ESMAP multi-tier framework for energy usage. Adapted from [10].

2.2 Distributed Grids

2.2.1 Topologies of distributed grids

A RES such as wind or solar has a unique generation profile which varies according to the availability of the source making the energy yield inconsistent. This inconsistency may lead to an energy shortcoming on a grid and is addressed in a different manner depending on the topology of the grid [11].

The topology of a distributed grid may be grid-tied or standalone. A grid-tied distributed grid is connected to the utility-grid and relies on the utility-grid to supply the energy shortcomings of the renewable sources. In the event that the energy yield from the RES is greater than the localised consumption, renewable energy is fed back into the utility-grid and can be transmitted through the transmission network to other regions for use or can be stored.

A standalone distributed grid operates off-grid and relies on ES systems to supply the energy shortcomings of the renewable sources. In the event that the energy yield from the RES is greater than the local consumption, the excess energy is stored in the ES

Table 2.1 Functional characteristics of well-known smart grids.

	AC or DC	Topology	Setting
Microgrid	Both	Grid-tied or Standalone	Industrial & Urban
Nanogrid	Both	Standalone	Urban & Rural
Picogrid	DC	Standalone	Rural or UPS

systems. If the capacity of the ES is full and the renewable energy yield is greater than the consumption, the grid control is then tasked with curtailing production. Due to the lack of a utility-grid in the targeted rural regions, a standalone topology is preferred for a rural electrification solution.

2.2.2 Existing Distributed Grids

There are several types of distributed grids. Examples of distributed grids are the Microgrid, Nanogrid and Picogrid. There are numerous existing solutions of each type of grid, each having a diverse range of operational metrics. It is sensible to distinguish between distributed grids according to the setting in which they are most suitably applicable and their functional characteristics as opposed to using metrics such as power capability and operational voltage. Table 2.1 distinguishes distributed grids according to a simplified set of functional characteristics and the setting where each type of grid is suited for.

A Microgrid can meet the minimum required capabilities for rural electrification and even surpass the extended capabilities. A Microgrid can provide large-scale industrial level electrification such as the Microgrids presented by [12], [13] and [14]. A Microgrid is thus not a pragmatic solution for small-scale rural electrification. It is more suited for large-scale urban electrification that can assist the utility-grid as discussed in [15–18].

A Nanogrid may serve as a possible solution for rural electrification such as the Nanogrid presented by [19]. A Nanogrid system can be deployed at multiple rural households and be interconnected to create a power-sharing network as shown by [20]. The Nanogrid solution presented by [21], [22] and [23] are standalone, DC distributed grids for urban household electrification. A Nanogrid may also be considered to be a small-scale Microgrid which assists a larger Microgrid for urban building electrification

as presented by [24]. A Nanogrid is suitable for small-scale, single urban household electrification, aiding an existing Microgrid or for single rural household electrification.

The concept of a Picogrid as presented by [1], is a distributed grid for single rural household electrification. The Picogrid presented by [25], serves as an uninterrupted power supply (UPS) for DC appliances during power outages. A Picogrid is described as a DC grid made up of "dumb" appliances and loads by [26]. Furthermore, [26] speaks of a Picogrid as a scaled down Nanogrid and that several Picogrids may be bundled together to form a Nanogrid. Work done by [27] presents a DC Picogrid as a preferred solution over battery backups with inverters and generators during power outages for appliances and low-power loads such as laptops in office buildings. A Picogrid is mainly used as a UPS solution for DC appliances during power outages. The majority of distributed grids for rural electrification are considered to be Nanogrids.

2.2.3 Control Architectures of Distributed Grids

The control architecture for a distributed grid may be centralised or decentralised. A hybridisation of the two architectures is also possible. A centralised architecture has a central controller which controls power flow on the grid at a global level. A dedicated communication network is required between elements connected to the grid and the controller. An advantage of centralised control is that complex control strategies may be implemented using this architecture which optimises power flow control on the grid [28]. This is because all of the distributed grid's data is at the disposal of the central controller. The major drawback to this architecture is that a single point of failure in the controller or communication network will affect the entire systems reliability [29, 11]. A centralised architecture is suitable for distributed grids where there are numerous parameters and data that needs to be considered and processed to control power flow. For example, on a large-scale distributed grid such as the urban Microgrid presented by [30] or a grid-tied Microgrid presented by [28].

A decentralised architecture obviates the need for a central controller and communications network by deploying a local control system at each element connected to the grid [31–33]. Each control system is required to operate autonomously and coordinate power flow with others on the grid. Due to the lack of a communications network, limited data from the distributed grid is available to each control system. This simplifies the decentralised control strategy compared to a centralised architecture

control strategy. This reduction in complexity brings about an increase in ease of implementation of the control strategy. Due to the lack of communications network, bus voltage signalling is used to infer information regarding the state of the grid as presented by [34–36]. The inferred information is used by the control system to make a decision on which control action to execute. This makes the bus voltage an information carrier and the single shared variable amongst all control systems on the grid [34, 37, 38, 35, 36]. A decentralised architecture overcomes the major drawback of a centralised architecture [29, 11]. A single point in failure on a decentralised architecture will affect only the control system concerned and the remainder of the distributed grid is isolated from the fault and continues to operate. A decentralised architecture is suitable for a distributed grid where there are few variables and minimal data that needs to be considered to control power flow. For example a small-scale Nanogrid for single rural household electrification as presented by [33] or a Nanogrid cluster for rural electrification as presented by [20].

A hybrid architecture is a combination of centralised and decentralised control architecture. A hybrid architecture deploys local control as well as makes use of a central controller and a communications network. From a hierarchical perspective, local control is the primary control which operates on a faster time scale than the central controller which is the secondary control. This architecture is suitable for the more complex distributed grids which have numerous functional characteristics that need to be considered to control power flow.

2.3 The Personal Consumer Grid

The PeCo grid was conceptualised as a standalone, ad-hoc, 12 V, DC distributed grid for single rural household electrification. The PeCo grid endeavours to provide a robust and resilient solution for rural electrification. Plug-and-play, scalability, low-cost and a flexible, ad-hoc architecture were sought after features for the PeCo grid. The PeCo grid is an interconnection of elements including PV or wind sources, batteries and loads. Each element is connected via an interface. At each interface, there is a DC-DC power converter, control platform and three grid connection ports. This concept is illustrated by Figure 2.2. A flexible and ad-hoc architecture is achieved via the three-port connection concept. The combination of an element and an interface is termed a block (as in building block) and blocks are classified as follows:

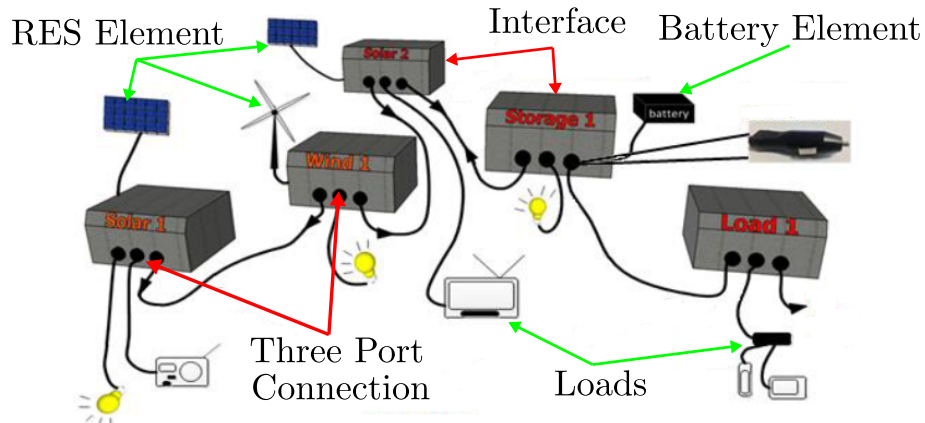


Fig. 2.2 PeCo grid with three-port connections at interfaces for a flexible architecture.

- Source element + Interface $\rightarrow$ GEN block
- Battery element + Interface $\rightarrow$ ES block
- Load element + Interface $\rightarrow$ Load block

Blocks are connected by a single line with both the negative and positive conductor using the DIN ISO 4165 connector, see Figure 2.3. This approach allows for the end-user to add or remove blocks in a plug-and-play manner to build an ad-hoc grid personalised for their power demands. Furthermore, this approach lends itself to scalability. Scalability under the context of the PeCo grid refers to scaling the grid's power capability, by adding or removing blocks. This makes growing and extending the grid uncomplicated for the end-user. Faults such as overloading or short-circuits should be dealt with transparently because the end-user is not expected to have any formal training to operate the grid. Even if by trial and error, a workable grid can be achieved by the end-user by incorporating a basic form of user interaction such as a happy or sad face displayed at each interface to indicate the status of a block. The PeCo grid should commission and operate autonomously when blocks are interconnected. For example, if a load and GEN or ES block are connected, each block will self-initialise and power flow will be controlled in an autonomous and coordinated manner with other blocks. Thereafter, the end-user can scale their system in an uncomplicated manner by adding or removing blocks at the three-port connector and the grid will deal with this in a transparent manner. This autonomous and coordinated control of power is accomplished by means of the nature-inspired control strategy of the PeCo grid.



Fig. 2.3 Single line connectors for the PeCo grid.

2.3.1 Biomimetic Intelligence

Biomimetics is the study and use of concepts found in nature to create biologically inspired technologies [39]. The control strategy for the PeCo grid was inspired by the social systems of social insect colonies such as bees and ants. The concept of stigmergy describes a mechanism of self-organising behaviour and coordination exhibited by social insect colonies. The idea is that work performed by an agent modifies the environment which then stimulates a response from the same or other agents in the environment with the aim of returning the environment to homeostasis [40]. This notion explains how colonies composed of simple insects with minimal intelligence collaboratively perform complex tasks without any apparent communication.

By taking a stigmergic agent-based approach a decentralised control architecture and control strategy could be achieved for the PeCo grid. Intelligence in the form of the control strategy is deployed at the interface of each block and executed by the local controller as opposed to there being a central controller for all blocks. Power flow is controlled in a coordinated manner with other blocks in response to modifications of the grid voltage. Additional advantages of taking a stigmergic approach are [1]:

- The internal state of each block is not required by other blocks to coordinate power flow which eliminates the need for related infrastructure.
- Sub-system tasks performed by each block contribute to achieving system-level outcomes which improve the flexibility and robustness of the PeCo grid.

Grid Voltage (V)		GEN Block	ES Block	Load Block	
	V_{max}	Shutdown	Shutdown	Shutdown	Over
	V_{nom}	Curtail Production	Charge Battery	Dispatch Load	Stable Region
	V_{min}	Increase Production	Discharge Battery	Shed Load	
		Shutdown/ Commission	Shutdown/ Commission	Shutdown/ Commission	Under

Fig. 2.4 Control action taken by a block based on the grid voltage sensed.

- Scalability is supported through the use of bounded agents, blocks, in a potentially unbounded environment, the PeCo grid.

2.3.2 Stigmergy Based Control Strategy

Blocks connected to the grid are agents that modify the PeCo grid environment. The single target variable that needs to be controlled is the grid voltage sensed by the local controller at the three port connection of a block. This makes the grid voltage the environmental factor that is modified and that stimulates responses from blocks.

The grids power status (power surplus or power deficiency) is inferred from the grid voltage via bus voltage signalling. The primary control objective is to ensure the grid voltage remains within a stable region bounded by a minimum and maximum voltage, V_{min} and V_{max} . Homoeostasis is thus achieved when the grid voltage is within the stable region. Once the grids power status is known, the controller is tasked with regulating power flow from the element to the grid to ensure the grid voltage remains in the stable region. This is accomplished by approaching a nominal grid voltage V_{nom} within the bounded region. The control action does not stabilise the grid voltage at V_{nom} and a level of fluctuation about V_{nom} is permitted to allow for blocks to monitor the events on the grid. Figure 2.4 illustrates the stable region of operation and the control action taken by a block based on the grid voltage.

A rise in grid voltage above V_{max} indicates an oversupply of power to the grid and a fall in grid voltage below V_{min} indicates an overload on the grid. If either is sensed, the control action is to shut down and cease power flow between the element and the grid. The block remains shut down for a time period. Once the shutdown time period has elapsed, the block will commission power flow. If the block is unable to commission, for example in the event that the overload or a fault condition persists, the block will return to shut down and after the shutdown time has elapsed, re-attempt commissioning. The block continues through this cycle until the overload or fault condition is resolved.

If the grid voltage is in the region bounded by V_{nom} and V_{max} , there is a power surplus on the grid. The control action taken by a block aims to decrease the grid voltage. A GEN block curtails power production, an ES block initiates battery charging and a load block dispatch's loads. If the grid voltage is in the region bounded by V_{min} and V_{nom} , there is a power deficiency on the grid. The control action taken by a block aims to increase the grid voltage. A GEN block increases power generation, an ES block discharges batteries to support the GEN block with power generation and a load block sheds loads.

2.3.3 Legacy Grid

Work done by [2] and [1] validated the key concepts of the PeCo grid. The Legacy Grid composed of four prototype blocks was built, see Figure 2.5. Testing validated the flexible and ad-hoc architecture of the PeCo grid and the plug-and-play scalability. The stigmergic based voltage control strategy was successfully implemented and blocks operated autonomously and coordinated their control of power flow. The three-port connection concept was implemented at the interface of each prototype block. A block diagram representation of the of a prototype block is depicted by Figure 2.6. The main hardware components at the interface are, a Flyback converter and a control platform. PV and wind sources were not interfaced to the grid. Instead, power was delivered from a DC power supply under controlled conditions. Power flow from the DC supply was controlled according to the stigmergic based control strategy executed by the control platform. The hardware technology at the interface is covered in further detail in Chapter 3.

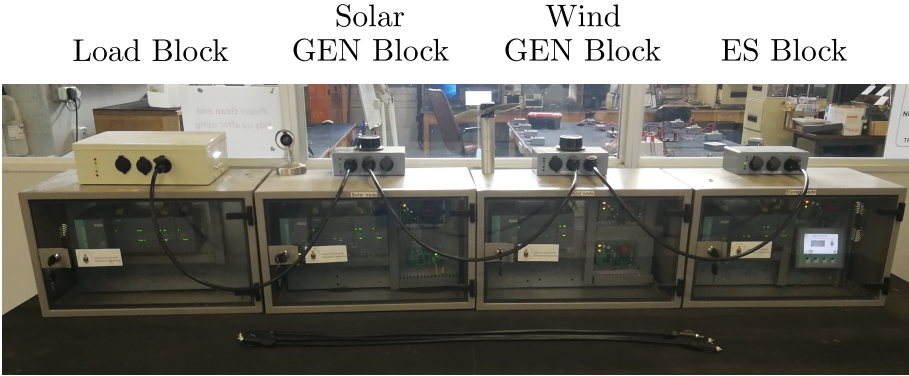


Fig. 2.5 Legacy Grid and the four prototype blocks.

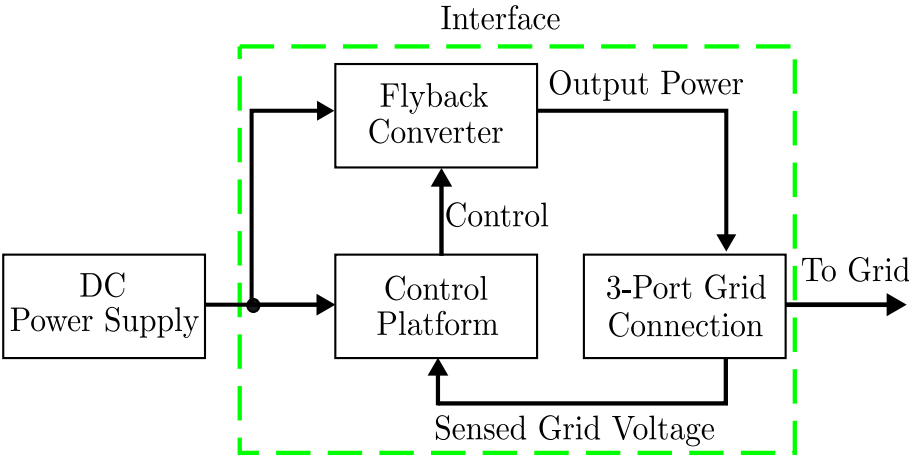


Fig. 2.6 Block diagram of the components of the prototype block.

2.4 Concluding Remarks

In this Chapter, the accomplishment of the first research objective was communicated. The foundation of background knowledge required to conduct this research was communicated.

Chapter 3

Hardware Technology at the Interface

The ultimate goal of the PeCo grid is to provide a viable electrification solution for rural households which can address the energy poverty crisis in rural regions of the world. To achieve this, an advancement of the hardware technology used for the Legacy Grid is needed. Suggestions given by [2] for advancing the hardware at the interface are:

- The hardware must cater for interfacing a PV module.
- The control platform must be replaced by a control platform solution that processes faster than the current solution.

This Chapter communicates the answer to the first research sub-question and the accomplishment of the second and third research objectives.

3.1 Flyback Converter

A DC-DC power converter is required at the interface of a PV module to the PeCo grid. Since the birth of the electronic age, the technology of the switch mode power supply (SMPS) topology has advanced to offer a clear advantage in size, cost and efficiency over linear supply technology. That being said, there are numerous SMPS topologies, classified as isolated or non-isolated. Consider an element interfaced to the PeCo grid. Isolating the element from the PeCo grid is an important safety and protection feature.

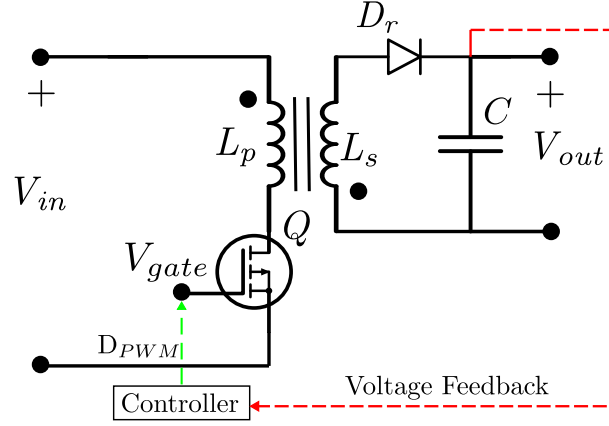


Fig. 3.1 Schematic of Flyback topology power converter.

Isolation protects from faults such as an over-voltage or a short-circuit on the PeCo grid and improves the robustness and resilience of the PeCo grid as a whole. The Flyback topology, see Figure 3.1, is one of the simplest and most popular isolated SMPS topology for low power applications (< 100 W). The popularity of the Flyback converter is due to its low component count and low-cost. This made the Flyback topology the preferred choice of power converter at the interface for elements on the Legacy Grid and was adopted for interfacing of a PV module to the PeCo grid.

3.1.1 Modes of Operation

The Flyback converter operates in an alternating ON and OFF state determined by the state of the MOSFET gate voltage, V_{gate} . V_{gate} is driven high and low by a PWM signal generated from a controller. Output voltage regulation can be achieved by adjusting the duty-cycle of the PWM signal, D_{PWM} according to a control strategy. The output voltage V_{out} is the process variable that serves as feedback to the controller. The controller compares V_{out} to a reference voltage V_{ref} . D_{PWM} is the control variable which is adjusted to ensure $V_{out} = V_{ref}$. The resulting Flyback converter circuit during the ON and OFF states is depicted by Figure 3.2. The key waveforms describing the operation of the Flyback converter during a switching period in discontinuous conduction mode (DCM) and continuous conduction mode (CCM) are illustrated by Figure 3.3 and Figure 3.4 respectively.

During the ON state V_{gate} is driven high and the MOSFET switch is closed. At the primary side: The input voltage V_{in} is applied across the primary inductor L_p . Primary

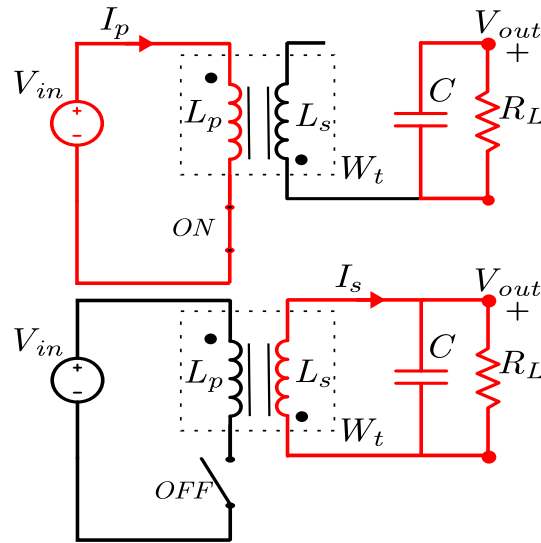


Fig. 3.2 Resulting Flyback circuit when MOSFET is switched ON and OFF.

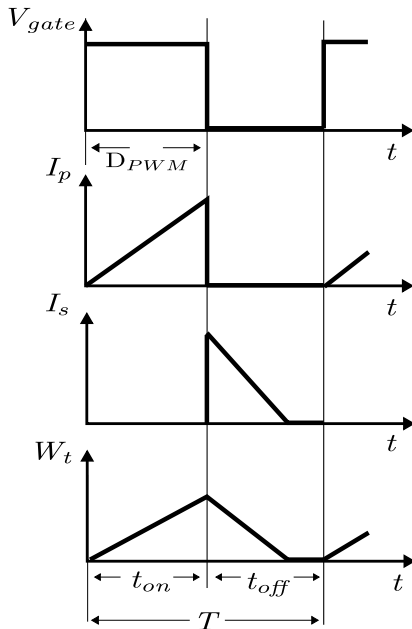


Fig. 3.3 Key waveforms of a DCM Flyback converter.

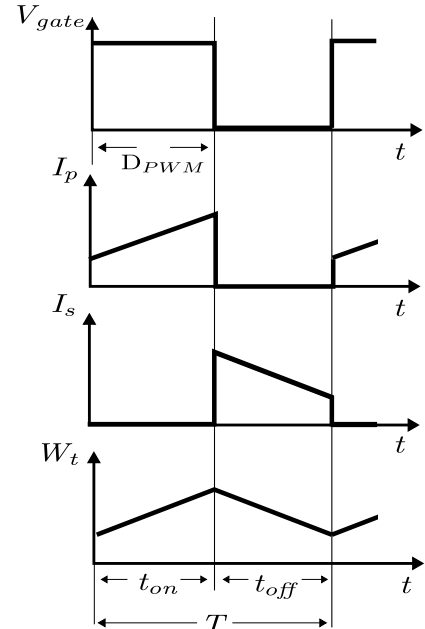


Fig. 3.4 Key waveforms of a CCM Flyback converter.

Table 3.1 Comparison of DCM to CCM.

	DCM	CCM
Core size	Small	Large
Losses	High	Low
Component stress	High	Low
Control	Simple	Complex
Transient response	Fast	Slow

side current I_p flows through L_p and the energy stored in the core W_t rises linearly over the ON time period t_{on} . At the secondary side: Diode D_r does not conduct due to the opposing winding of the inductors. Energy stored in the output capacitor C is delivered to the load R_L .

During the OFF state, V_{gate} is driven low and the MOSFET switch is open. No current flows through the primary side. At the secondary side: D_r conducts, secondary side current I_s flows through the secondary side inductor L_s and the energy stored in the core during the ON state decreases linearly over the time period t_{off} . Energy is delivered to R_L and stored in C for the next switching cycle.

When operating in DCM, the inductors have zero energy at the start and end of the switching period T . All the energy stored in the core is transferred to the load before the next switching period begins. When operating in CCM, the inductors have residual energy at the start and end of T . The core does not fully dissipate the stored energy before the next switching period begins. The choice of operating mode is dependant on the application of the Flyback converter. Table 3.1 compares a Flyback operating in DCM to CCM. Operating the Flyback converter in DCM was preferred on the Legacy Grid. The higher efficiency and lower component stress of CCM were traded-off for the simpler control, faster transient response to changes in load and reduced core size of DCM. DCM operation was adopted for interfacing a PV module to the PeCo grid.

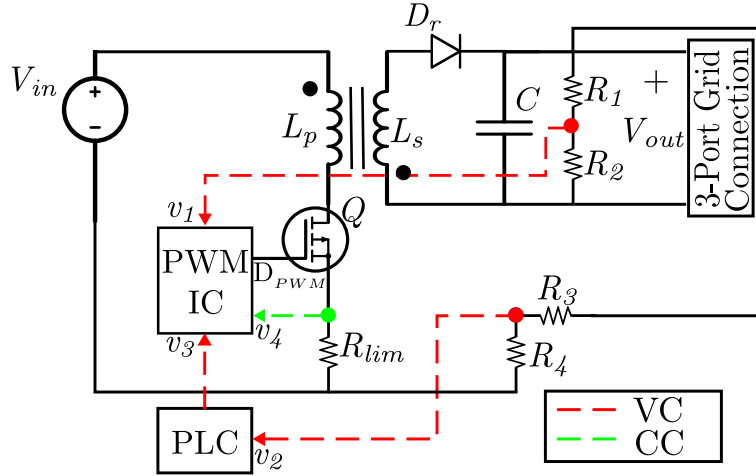


Fig. 3.5 Schematic of the main components at the interface of a Legacy Grid prototype block.

3.2 Legacy Grid Hardware

3.2.1 Power Source

The Legacy Grid did not interface actual PV modules, wind turbines or battery elements. Sources were emulated by DC power supplies. The DC power supply used was the Siemens SITOP PSU100S 24 V/ 10 A DC power supply and was preferred for its compatibility with the Siemens PLC. The Siemens power supply was not adopted for interfacing a PV module to the PeCo grid.

3.2.2 Control Platform

The main components comprising the control platform are a Siemens Simatic S7-1200 PLC and a UC3825 PWM integrated circuit (IC). The PLC is the digital component of the control platform and the PWM IC is the analogue component. Figure 3.5 depicts the interconnection of the control platform and the Flyback converter. The control platform was tasked with current control (CC) for over-current protection and voltage control (VC) for regulating the output voltage according to the control strategy executed by the PLC.

Table 3.2 Control action achieved according to the change in D_{PWM} .

Control action	Duty-cycle adjustment
Increase production	$D_{PWM} ++$
Curtail production	$D_{PWM} --$
Shutdown	$D_{PWM} = 0$

Over-current protection was achieved using a sense resistor R_{lim} to measure I_p . The voltage sensed across R_{lim} is input to the current limit pin of the PWM IC as voltage signal v_4 . The current limit of the PWM IC, V_{lim} is set according to a hardwired resistor configuration. If $v_4 \geq V_{lim}$ evaluates to true, the PWM IC sets $D_{PWM} = 0$.

To achieve output voltage regulation, the status of the grid's power is inferred by sensing V_{out} at the three-port connector. Voltage dividers $R1/R2$ and $R3/R4$ scale down V_{out} to the input ranges of the PWM IC and PLC as signals v_1 and v_2 respectively. The PLC processes v_2 according to the voltage control strategy and outputs a control signal v_4 to the PWM IC. v_4 is compared to v_1 by the PWM IC which then implements the control action of varying D_{PWM} . The control action achieved by adjusting D_{PWM} is summarised in Table 3.2.

3.2.3 Hardware Realisation

The hardware realisation of the control platform and Flyback converter at the interface of the Legacy Grid GEN block are depicted by Figure 3.6. The PWM IC is placed onboard with the Flyback converter components whereas the PLC is off-board. The PWM IC is configured to operate by a set of hardwired components depicted in Figure 3.6b. Several different configurations were hardwired and jumpers were used to select a configuration. This limited the flexibility of the control platform as the configuration cannot be easily modified and to implement new configurations requires a new board to be designed. The PLC depicted in Figure 3.6a is a sizeable component compared to the Flyback converter and PWM IC. The size and cost of the PLC make it impractical as a control solution for the PeCo grid. The control strategy is simple and can be executed on a micro controller unit (MCU). Furthermore, the MCU can be designed to be onboard with the Flyback converter and this will consolidate the PLC and PWM IC into a single digital control solution.

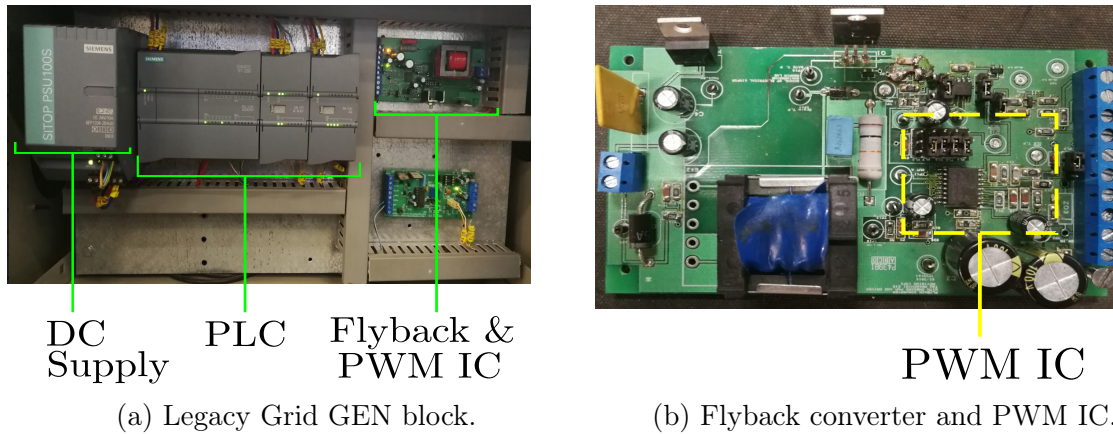


Fig. 3.6 Hardware realisation of the Legacy Grid GEN block highlighting the hardwired PWM IC and configurations.

3.3 Hardware Adaptation

The Flyback converter was adopted from the Legacy Grid and the following adaptations were made:

- A new transformer was designed to interface a PV module to the PeCo grid.
- The PWM IC and the PLC connections were removed from the board and the board design adapted to cater for an onboard MCU.

The snubber design, MOSFET driver IC and the isolation amplifier IC used for isolated feedback of V_{out} were adopted from the Legacy Grid Flyback converter. The switching frequency was kept at 50 kHz.

3.3.1 Transformer Design

The transformer design parameters are selected to cater for interfacing the SLP030-12U PV module. This PV module was selected as an entry-level, low-power PV module for end-users to purchase with an interface to the PeCo grid. The power capability of this PV module is sufficient to achieve basic lighting and cell-phone charging. The PV module parameters are listed in Table 3.3.

An E30 ferrite core was used for the Legacy Grid's Flyback converter. To reduce cost and size, an E25 ferrite core was selected for the design of the PV module transformer.

Table 3.3 Specifications of the SLP030-12U PV module.

Parameter	Value
Maximum power (P_{mpp})	30 W
Voltage at P_{mpp} (V_{mpp})	17.2 V
Current at P_{mpp} (I_{mpp})	1.74 A
Open-circuit voltage (V_{oc})	21.6 V
Short-circuit current (I_{sc})	1.93 A

Table 3.4 Design parameters of the transformer and core properties.

Parameter	Value
Rated Power (P_{rated})	40 W
Frequency (f)	50 kHz
Maximum duty-cycle D_{max}	48%
Input voltage (V_{in})	17.2 V
Output voltage (V_{out})	12.5 V
Average input current (I_{in})	2.33 A
Average output current (I_{out})	3.2 A
E25 Core flux density (B_{max})	0.3 T
E25 Core area (A_{core})	52.5 mm ²
E25 Core mean flux length (l_{core})	57.7 mm
E25 Core volume (V_{core})	3020 mm ³
Relative permeability (μ_r)	1000

The design parameters of the transformer and core properties are listed in Table 3.4. The rated power of the transformer was set to $P_{rated} = 40$ W. This would ensure sufficient functionality of the transformer for interfacing the 30 W PV module.

The transformer is required to cater for a wide range of input voltages. V_{in} will vary according to the temperature of the PV module and the availability of solar irradiance. To ensure peak efficiency is delivered when the PV module is operating at maximum power, the transformer is designed for an input voltage of $V_{in} = V_{mpp}$. The transformer is required to cater for a wide range of output voltages. V_{out} will vary according to changes in load conditions on the grid. To ensure peak efficiency is delivered when the grid is operating in the stable region, the transformer is designed for an output voltage of $V_{out} = V_{nom}$.

Inductor Design

The design process begins by determining the inductance of coupled inductors, $L_{p/s}$. The peak current through the inductor, when operated in DCM is expressed by:

$$I_{peak} = 2 \times D_{max} I_{ave} \quad (3.1)$$

where:

I_{ave} = The average current through the inductor during a switching cycle.

The total energy per pulse to be stored by the transformer is expressed by:

$$E_{PerPulse} = \frac{P_{rated}}{f} \quad (3.2)$$

The energy stored in the inductor is expressed by:

$$E_{ind} = \frac{1}{2} L I_{peak}^2 \quad (3.3)$$

By substituting equations 3.1 and 3.2 into equation 3.3, the inductance values were calculated using:

$$L = \frac{2E_{pp}}{I_{peak}^2} \quad (3.4)$$

Air Gap

After determining the inductor values, the maximum energy that can be stored in the ferrite core was calculated using:

$$E_{CoreMax} = \frac{B_{max}^2 V_{core}}{2\mu_0\mu_r} \quad (3.5)$$

where:

$$\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2.$$

If $E_{CoreMax} < E_{PerPulse}$, then an air gap must be introduced to the core to store the energy that the core cannot. The energy stored in the air gap was calculated using:

$$E_{gap} = E_{PerPulse} - E_{CoreMax} \quad (3.6)$$

The length of the air gap required to store E_{gap} was calculated using:

$$l_{gap} = \frac{2E_{gap}\mu_0}{B_{max}^2 A_{core}} \quad (3.7)$$

Turns Ratio

The final step for the transformer design was to determine the number of turns required for each inductor and the cross-sectional area of conductor required to conduct the peak current. The number of turns was calculated using:

$$N = \sqrt{L \left(\frac{l_{core}}{A_{core}\mu_0\mu_r} + \frac{l_{gap}}{A_{core}\mu_0} \right)} \quad (3.8)$$

The required area of the conductor used to construct the the inductors was calculated using:

$$A_{wire} = JI_{ave} \quad (3.9)$$

where:

J = The current density of the conductor.

The design parameters of the transformer for interfacing the PV module are listed in Table 3.5.

Table 3.5 Design parameters of transformer for interfacing the PV module.

Parameter	Value
Primary inductor (L_p)	19.6 μH
Secondary inductor (L_s)	9 μH
Air gap length (l_{gap})	0.38 mm
Number of turns for L_p (N_p)	11.5
Number of turns for L_s (N_s)	8.5

3.3.2 Transformer Construction

Power losses are taken into consideration when constructing a transformer. The choice of materials and method of construction were aimed at minimising the following: winding loss, core loss and stray loss. Appendix A gives an overview of transformer losses and how losses are influenced by the construction and choice of materials.

Inductor construction

The properties of the conductor selected for the inductor construction are listed in Table 3.6. These were sourced from the chart of American Wire Gauge (AWG) wire sizes and current rating [41]. The choice of conductor influences the winding loss of the transformer. The cross-sectional area of conductor required for each inductor was calculated from equation 3.9. Several strands of conductor were twisted together to achieve the calculated area of conductor for each inductor. The number of strands of conductor required to achieve the cross-sectional area was calculated from equation 3.10 and are listed in Table 3.6.

$$Strands = \frac{\sqrt{A}}{\pi r_{con}} \quad (3.10)$$

Inductor Winding

Figure 3.7 illustrates three winding methods for an E-geometry core. The winding method influences the coupling between the inductors and the stray loss. The choice of core geometry and material influences the core losses. In winding method A, the

Table 3.6 Conductor properties.

Parameter	Value
Material	Copper
AWG Gauge	30
Rated current max	0.142 A
Radius (r_{con})	0.127 mm
Cross sectional area (A_{con})	0.0507 mm ²
Current density (J_{con})	2.8 A/mm ²
Area of conductor for L_p (A_p)	1.8 mm ²
Area of conductor for L_s (A_s)	2.67 mm ²
Number of strands for L_p	5
Number of strands for L_s	6
Length of conductor for L_p (l_p)	565 mm
Length of conductor for L_s (l_s)	375 mm

primary inductor is wound and the secondary inductor wound over it. In winding method B, the secondary inductor winding is sandwiched between the primary inductor winding. This is achieved by winding half of the turns of the primary inductor, then winding the secondary inductor and finally completing the primary inductor winding over the secondary. In winding method C, the primary and secondary inductors are combined to form a combined winding. Method C complicates achieving the required number of turns of each inductor. When the number of turns for the shorter winding is achieved, the combined winding must split and the remaining turns of the longer winding are wound over the combined winding.

A transformer was built using each winding method. The coupling coefficient of each was calculated from equation 3.11. The inductance values were measured using the BK Precision® 300 kHz LCR meter. Table 3.7 compares the coupling of each winding method and method B achieved the best coupling.

$$k = \sqrt{1 - \frac{L_{short}}{L_{open}}} \quad (3.11)$$

where:

L_{short} = The inductance measured across a wound inductor with the other inductor shorted.

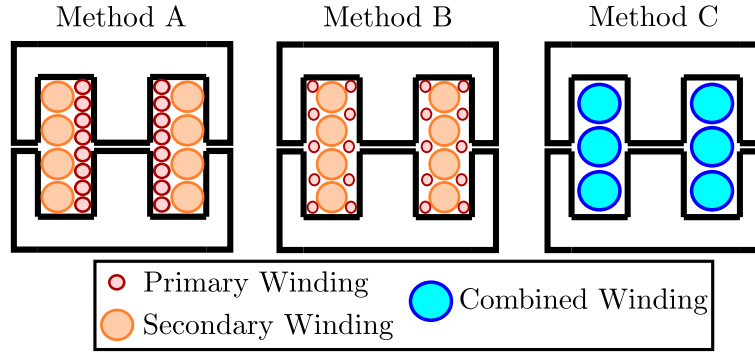


Fig. 3.7 Winding methods for E-geometry transformer core.

Table 3.7 Coupling coefficient of each winding method.

Method	k
Method A	96.3%
Method B	98.8%
Method C	94.8%

L_{open} = The inductance measured across the same inductor with the other inductor left open.

3.4 Flyback Converter Board Design

Figure 3.8 depicts a rudimentary schematic of the main components comprising the Flyback converter board designed to cater for the MCU control platform. The PWM IC, jumper configurations and the connections for the PLC to the board were removed. The components comprising the control platform are:

- Voltage dividers R_3/R_4 and R_1/R_2 .
- 12 V and 3.3 V voltage regulators.
- MCU.
- Driver IC.
- Isolation amplifier (A).
- DC-DC converter B .

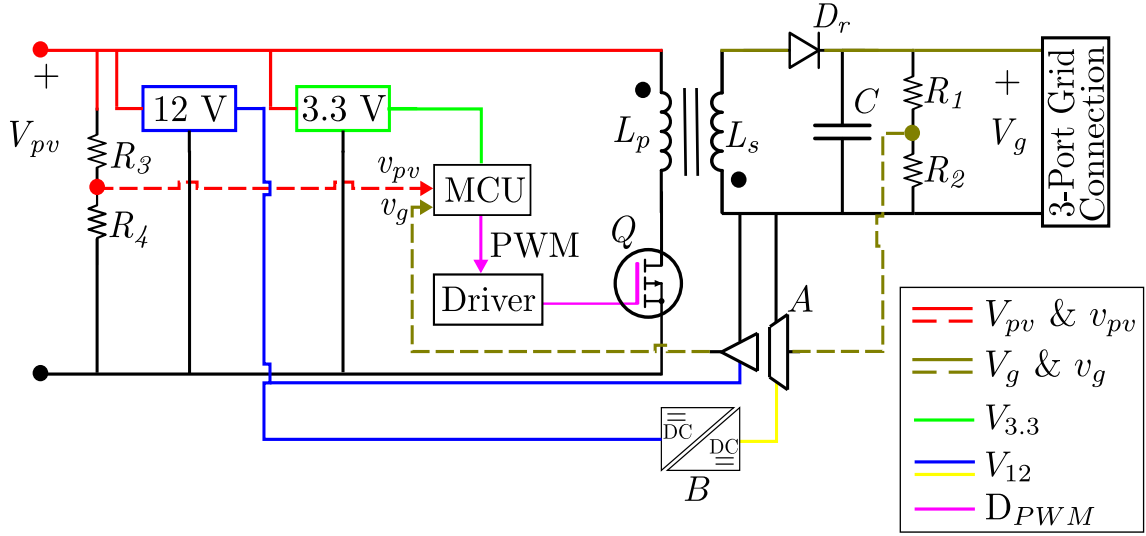


Fig. 3.8 Rudimentary schematic of the Flyback converter with an onboard MCU.

The bill of materials, detailed schematic and printed circuit board of the complete board design is given in Appendix B.

3.4.1 Micro-Controller Unit

The MCU selected was the C2000TM TMS320F28027 PiccoloTM manufactured by Texas InstrumentsTM (TI) [42]. As stated in the application note [42], this MCU was designed and is suited for grid infrastructure applications and was selected for the following features:

- An enhanced PWM peripheral.
- 12 Bit analogue-to-digital (ADC) converter.
- Low cost.
- Low power.
- Low profile and Small size.
- A unique software development environment and toolchain.

TI and MathWorks[®] offer a unique software development environment and toolchain for designing, testing, evaluating and the eventual execution of digital control strategies.

This software permits for a model-based approach to be taken for designing the control strategy. The control strategy can be modelled as a state diagram in software. The software generates the code for the model and uploads it as an executable file to the MCU. This feature simplifies the development of the control strategy. Furthermore, the control strategy is digitised and any modifications can be implemented by simply changing variables in software. This feature enhanced the flexibility of the control platform compared to the hardwired configurations of the PWM IC.

Debug probe

Debug communications to the MCU is achieved using the XDS110 debug probe. The board design features a standard CTI-20 connector at the debug interface for the XDS110 to communicate with the MCU. Details on how to connect the debug interface to the MCU are given in [43].

3.4.2 ADC Inputs and PWM Output

The PV module voltage, V_{pv} and the grid voltage, V_g are scaled down to the 0-3.3 V input range of the MCU ADC by voltage dividers R_3/R_4 and R_1/R_2 respectively. The scaled voltage signals, v_{pv} and v_g , are the only input signals to the MCU. V_{pv} is an input parameter for MPPT and V_g is an input parameter to infer the grid's power status. The single output from the MCU is a PWM signal to the driver IC.

3.4.3 Isolated Feedback

The ADuM3190 isolation amplifier manufactured by Analog Devices was adopted from the Legacy Grid for isolated feedback of V_g to the MCU. The ADuM3190 exhibits voltage output linearity within the 0.4 V - 2.1 V range [44]. This limits the input range of v_g and reduces the resolution of v_g from 0.805 mV to 0.513 mV. The ADC resolution was calculated from equation 3.12. This loss in resolution reduces the accuracy of the control which revolves around accurate and precise measurement of V_g . Furthermore, the cost of the ADuM3190 does not warrant its use and a more accurate and lower cost isolated feedback solution should be implemented in future research.

$$V_{\text{res}} = \frac{V_{\text{ADC}_{\text{max}}}}{2^n} \quad (3.12)$$

where:

V_{res} = ADC resolution.

$V_{\text{ADC}_{\text{max}}}$ = Maximum voltage input to the ADC.

n = ADC bits.

3.4.4 Voltage Supply

A 3.3 V regulated supply is added to the board to power the MCU. A 12 V regulated supply is added to the board to power the isolation amplifier and MOSFET driver IC. The isolated DC-DC converter transfers the 12 V supply to the secondary side of the board to supply the secondary side of the isolation amplifier.

3.4.5 Hardware Realisation

Figure 3.9 depicts the hardware realisation of the Flyback converter with an onboard MCU. The MCU consolidates the PLC and PWM IC into a single digital solution and drastically reduces the size of the interface, see Figure 3.10a.

The MC4 connector was added to the design for connecting a PV module to the Flyback converter. This ensures that the end-user cannot incorrectly connect the PV module. The three-port connector was adopted from the Legacy Grid. An installed interface is depicted by Figure 3.10b.

3.5 Power and Efficiency Test

This test was conducted to establish the power capability and the efficiency of the Flyback converter under varying load conditions. A DC power supply, V_{DC} was interfaced to a 12 V lead acid battery, V_{bat} , via the Flyback converter see Figure 3.11. V_{bat} acts as a sink for the output power and obviates the need for a variable resistive

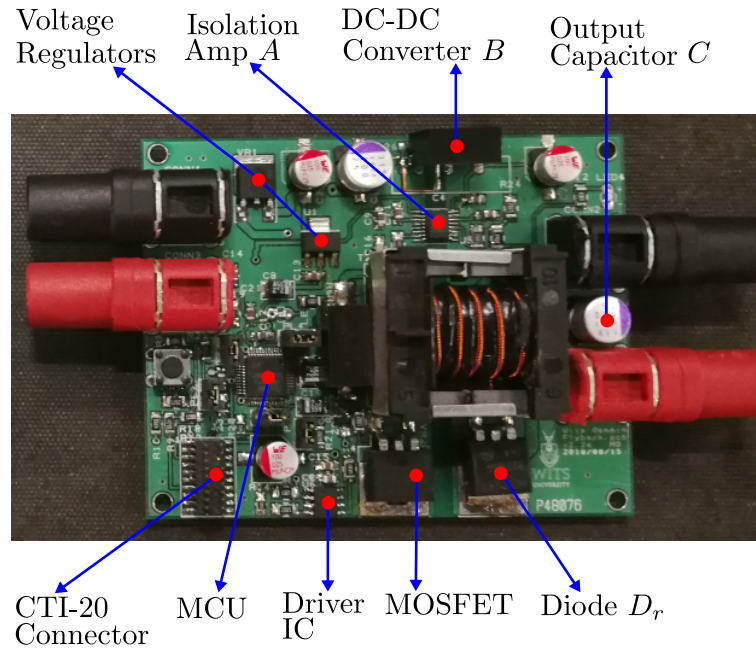
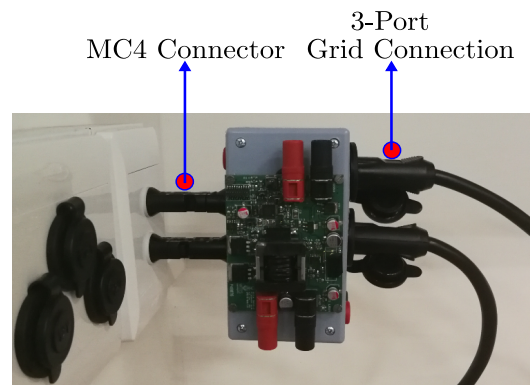


Fig. 3.9 Hardware realisation of Flyback converter with an onboard MCU.



(a) Size comparison.



(b) Installed interface.

Fig. 3.10 Size comparison of the Legacy Grid hardware to the new hardware and an installed interface.

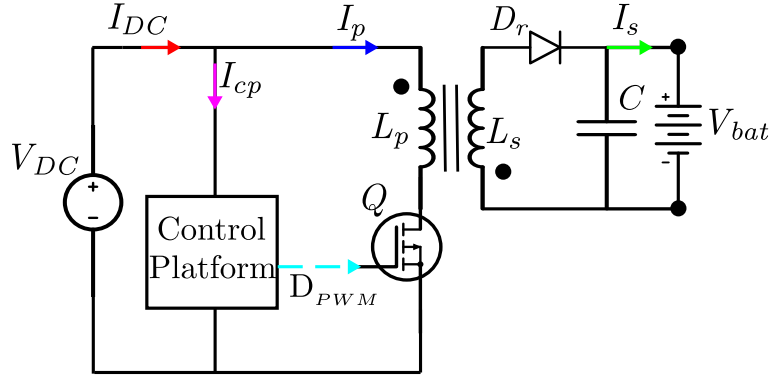


Fig. 3.11 Schematic of the circuit for the power and efficiency test.

load at the output. V_{DC} was set to 17.7 V and the supply current, I_{DC} , was limited to 2.33 A to ensure the rated power of the transformer, $P_{rated} = 40$ W, was not exceeded.

The process depicted by Figure 3.12 was modelled in software and uploaded to the MCU. D_{PWM} was incremented in steps of 0.5% until P_{rated} was delivered. D_{PWM} was limited to $D_{max} = 48\%$. The temperature of the board, T_{board} was measured at P_{rated} using an infrared thermometer. The current drawn by the control platform, I_{cp} , was measured and is the no-load power of the Flyback converter. The currents through the inductors, I_p and I_s were measured and logged at each increment of D_{PWM} to calculate input and output power, P_{in} and P_{out} using equation 3.13. All voltage and current measurements were taken using the Textronix MDO304 oscilloscope.

$$P_{in/out} = V_{DC} \times I_{p/s} \quad (3.13)$$

The efficiency of the Flyback converter was calculated from:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (3.14)$$

3.5.1 Results

Figure 3.13 depicts the results of the temperature measured at various regions of the board. Figure 3.14 depicts a plot comparing P_{in} and P_{out} to D_{PWM} . Figure 3.15 compares P_{in} and P_{out} to the efficiency. The average η for various load conditions

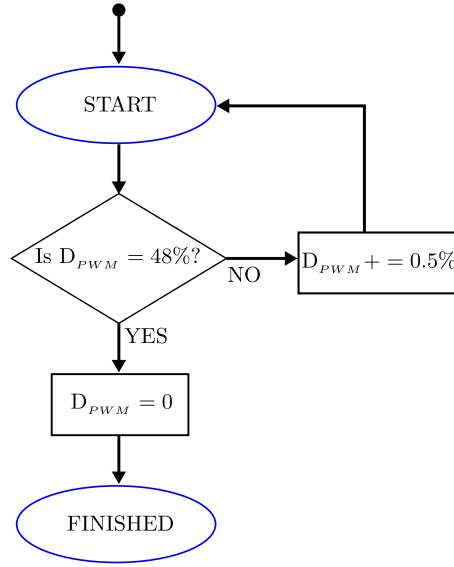


Fig. 3.12 UML diagram of the process executed by the control platform for the power and efficiency test.

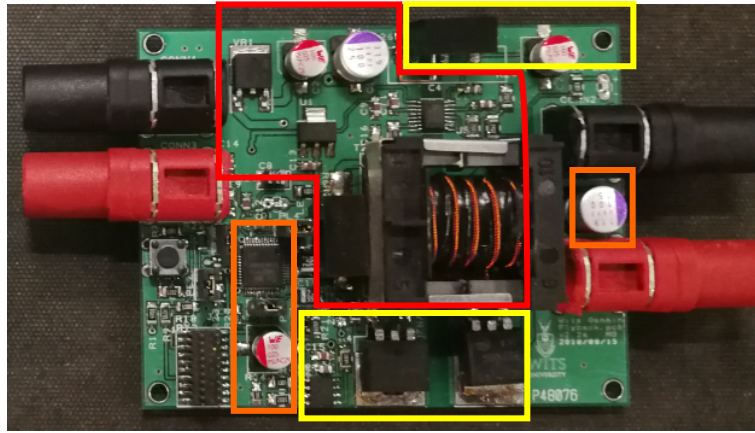
Table 3.8 Load condition and resultant output power and efficiency of the Flyback converter.

$P_{in}(W)$	$P_{out}(W)$	Average η	Load condition	% of P_{rated}
0.7- 6	0.04 - 4	55%	Light load	2 - 15%
6 - 33	4 - 25	76%	Moderate load	15 - 82.5%
33 - 40	25 - 30	74%	Heavy load	82.5 - 100%
0 - 40	0.04 - 30	70%	All loads	15 - 100%

is given in Table 3.8. Load conditions were classified into ranges based on the peak efficiency threshold, $\eta_{peak} = 76\%$. η_{peak} was delivered under moderate load conditions. $\eta < \eta_{peak}$ was delivered under light and heavy load conditions. At P_{rated} , $\eta = 73\%$ and at the MPP of the PV module, $P_{MPP} = 30W$, $\eta = 75\%$. The current drawn by the control platform, $I_{cp} = 0.1378$ A.

3.5.2 Discussion

The Flyback converter achieved peak efficiency deliverance at P_{MPP} which fell within the range of moderate load conditions. Efficiency was low when operating outside of moderate load conditions and the most drastic degradation occurred under light



 $75^{\circ}\text{C} \leq T_{board} \leq 90^{\circ}\text{C}$

 $50^{\circ}\text{C} \leq T_{board} \leq 55^{\circ}\text{C}$

 $30^{\circ}\text{C} \leq T_{board} \leq 35^{\circ}\text{C}$

Fig. 3.13 Board temperature measured at P_{rated} .

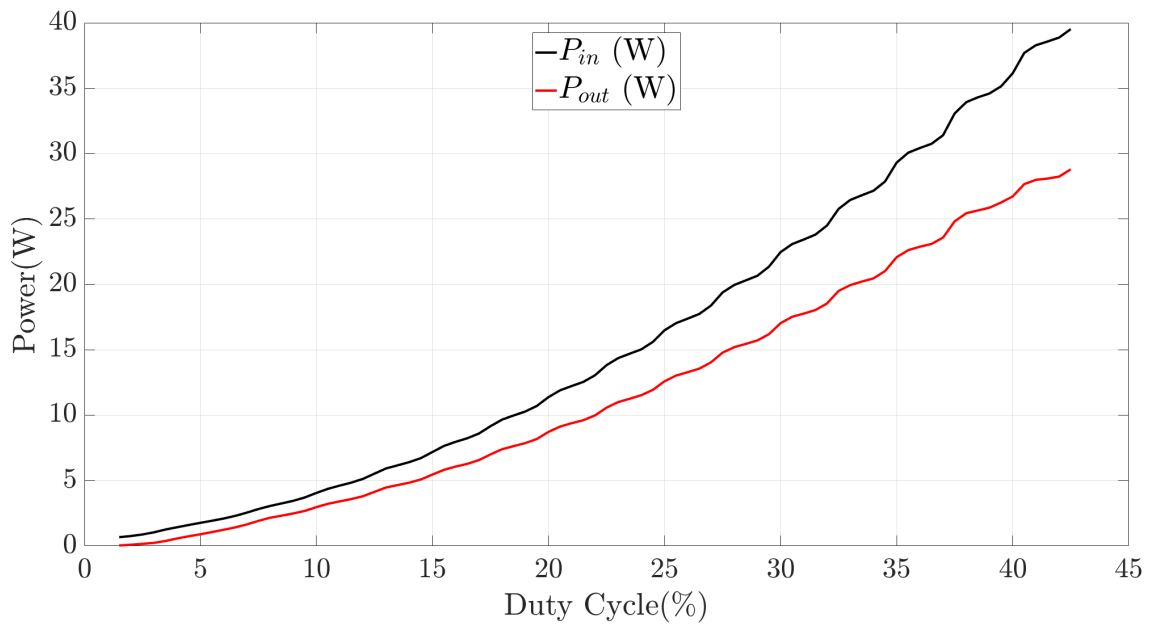


Fig. 3.14 Comparison of input and output power to duty-cycle.

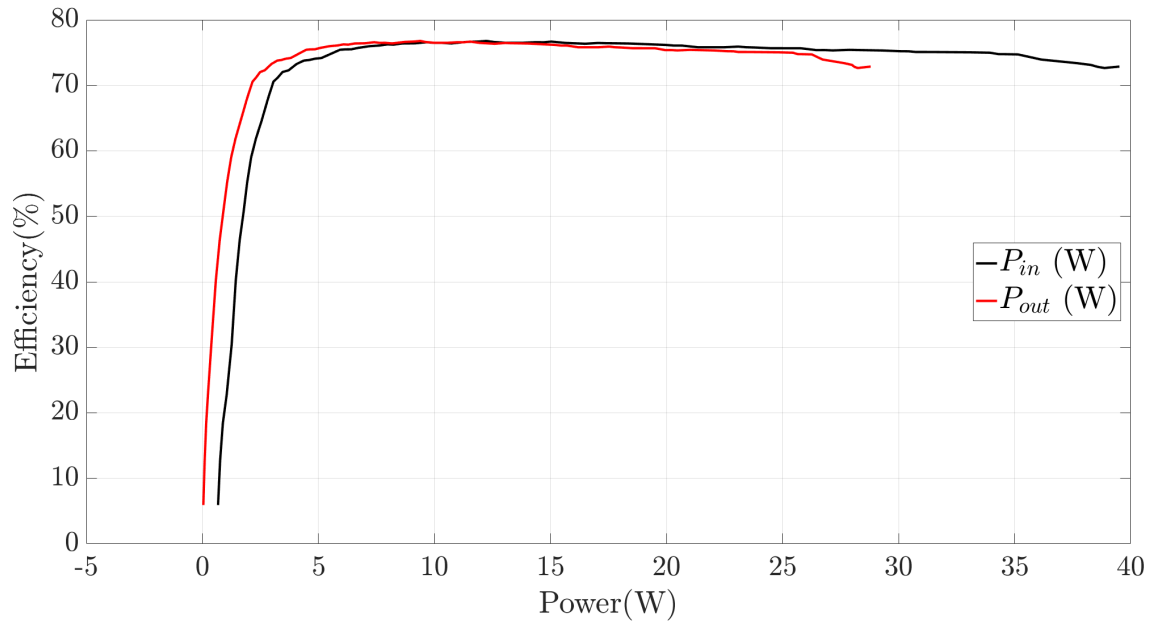


Fig. 3.15 Efficiency of the Flyback converter.

load conditions. The average efficiency under heavy load conditions was 2% less than moderate load conditions.

The efficiency under light load conditions can be improved by operating at a lower switching frequency. However, a larger core and inductors will be required. Alternatively, a recommendation for future research is that the switching frequency and switching losses of the Flyback converter can be scaled down with load demand. This is known as pulse frequency modulation (PFM). This can be achieved by modulating the frequency of the signal from the MCU driving the MOSFET relative to D_{PWM} which serves as an indication of load demand.

The power loss of the linear voltage regulators does not warrant their use. The heat dissipated by the regulators raised the temperature of the primary-side to a maximum of 90°C. Ideally, a thermal photograph of the Flyback converter should be taken to accurately illustrate the board temperature. Unfortunately, a thermal camera was not available for this research.

The hardware is expected to eventually be deployed in rural Africa and won't be operating under open air conditions. The closed air condition will further raise the temperature of the board which leaves it susceptible to thermal shutdown. A recommendation for future research is that the board design caters for a low power

onboard, multi-output Flyback converter to replace the regulators. The onboard MCU can provide the PWM signal for this Flyback converter and each regulator can be replaced by an output. The Flyback converter is suggested because it is suited for the wide input voltage range that the PV module will provide.

A recommendation for future work is to change the transformer design from wire-wound to planar magnetics. The planar magnetics will improve the efficiency of the Flyback converter by reducing transformer losses. Work done by [45] and [46] discusses the advantages of planar magnetics.

3.6 Concluding Remarks

The first research sub-question asked was:

"What technology from the Legacy Grid can be adopted for interfacing a PV module to the PeCo grid and what are the required adaptations to the technology for this purpose?"

The Flyback converter operating in DCM was adopted from the Legacy Grid. Adaptations to hardware included: A transformer design to interface a PV module and the board design was adapted to cater for an onboard MCU. The PLC and PWM IC connections and components were removed. The MCU consolidated the control platform into a single digital solution and drastically reduced the size of the hardware at the interface.

Shortcomings of the hardware are:

- There is a loss in resolution of the grid voltage caused by the limited linear output voltage range of the isolation amplifier.
- The efficiency under lightly loaded conditions is poor.
- Heat dissipation from the voltage regulators increased the board temperature.

In this Chapter, the need for a DC-DC converter to interface a PV module to the PeCo grid was communicated. The MCU control platform was selected as the control platform solution to replace the Legacy Grid control platform. The accomplishment of the second and third research objectives was communicated.

Chapter 4

Model-based Inductor Current

The inductor current of a power converter is required for the following applications: over-current protection, current-mode control and as reported by [47], to perform load-dependent mode switching. Inductor current sensing or estimation is thus key. In this Chapter, a mathematical model for the primary-side inductor current of a DCM Flyback converter is derived. In Chapter 6 the model is applied to perform model-based MPPT. This Chapter communicates the accomplishment of the fourth research objective.

4.1 Inductor Current Sensing Techniques

4.1.1 Sense Resistor Technique

The conventional current sensing technique is to place a sense resistor in series with the inductor. The current flowing through the inductor is determined by sensing the voltage drop across the resistor and applying Ohm's law. This technique is simple to implement as it only requires one additional component. The drawbacks of this technique are:

- It is invasive and the board design must cater for integration of the sense resistor.
- The power dissipated across the resistor is power lost. This reduces the efficiency of the power converter.

- Temperature increases at higher load currents will cause a change of resistance and reduce the accuracy of this technique.

The sense resistor technique is a simple current sensing solution for all applications. The accuracy drawback may be overcome by selecting a resistor material with a suitable temperature coefficient and power rating for the application [48]. However, high power sense resistors can be a sizeable and costly component. The power loss of this technique is a major drawback and other techniques that aim to address this are classified as loss-less techniques.

4.1.2 MOSFET sensing technique

MOSFET sensing is a popular loss-less technique for over-current protection due to its power efficiency and lack of an additional current sensing component. This technique estimates the inductor current by sensing the drain-source voltage, V_{DS} of the MOSFET, see Figure 4.1. When ON, the MOSFET behaves as a resistor, R_{DS} . Assuming a small V_{DS} , the equivalent R_{DS} is expressed by equation 4.1 [49, 50]. The inductor current can then be estimated using Ohm's law from V_{DS} and R_{DS} .

$$R_{DS} = \frac{L}{\omega \mu_m C_{ox} (V_{GS} - V_T)} \quad (4.1)$$

where:

L = The inductance.

$\omega = 2\pi f$.

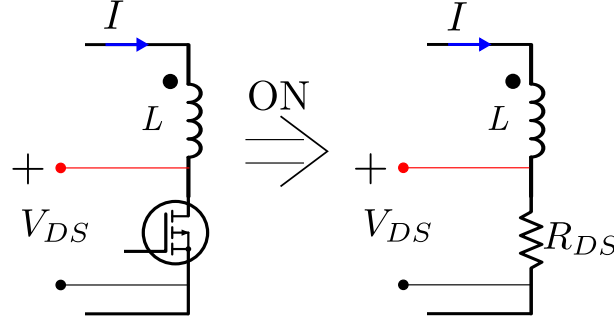
μ_m = The mobility.

C_{ox} = The oxide capacitance per unit area.

V_{GS} = The gate-source voltage.

V_T = The threshold voltage.

This technique is simple, efficient and no additional current sensing components need to be integrated into the power converter. However, this technique has low accuracy. The R_{DS} of the MOSFET is non-linear and has an exponential dependence on

Fig. 4.1 R_{DS} sensing and equivalent ON circuit.

temperature [48]. Low accuracy makes this technique unsuitable for control applications such as current-mode control and MPPT.

4.1.3 Other Loss-less Techniques

There are numerous other loss-less techniques for inductor current sensing. The methodology, application, advantages and drawbacks of these techniques are covered in work done by [49], [48] and [51]. The drawbacks of these techniques compared to the sense resistor and MOSFET sensing techniques are their cost, complexity and requirement to integrate several additional components or circuits into the power converter design. The application of these techniques is suited for current-mode control which is not even a requirement for this research. That said, it is not necessary to comprehensively review these techniques.

4.2 Model-based Technique

The sense resistor technique was considered most suitable for over-current protection in the prototype hardware. Efficiency was traded for lower cost, simplicity and better accuracy over the MOSFET technique. The sense resistor technique was considered for this research. However, the model-based technique presented by [52] offered a potentially accurate solution that could overcome the efficiency drawback of the sense resistor technique. The premise for a model-based technique is to create a model of the system from knowledge of the relationship between system parameters and their state. Consider the voltage-current relationship of an inductor:

$$V(t) = L \frac{dI}{dt} \quad (4.2)$$

where:

$V(t)$ = The instantaneous voltage across the inductor.

dI/dt = The rate of change of current with time flowing through the inductor.

By integrating equation 4.2 the inductor current can be estimated from knowledge of the inductance and the voltage across the inductor:

$$I = \frac{1}{L} \int_0^t V(t) dt + I_0 \quad (4.3)$$

where:

I_0 = The initial current flowing through the inductor at $t = 0$.

Work presented by [52] derives a model based on equation 4.3 to reconstruct the inductor current from the inductor voltage for non-isolated topology power converters including Buck, Boost, Buck-Boost, Boost-buck and single-ended primary-inductor (SEPIC). The model-based technique is applied to estimate the inductor current for current-mode control and dramatically enhanced the noise and load range compared to conventional techniques [52, 53].

4.2.1 Model Derivation for a Flyback Converter

A model for the primary-side inductor current of a DCM Flyback converter could not be found in literature and thus had to be derived. Current will only flow through the primary side inductor during the ON state. This is illustrated by Figure 4.2 and the current waveform is illustrated by Figure 4.3. During the ON state, current I_p flows through L_p and rises linearly to a peak value I_{peak} over the ON time period t_{on} . The value of I_{peak} was derived from equation 4.3 and is expressed by:

$$I_{peak} = \frac{V \times t_{on}}{L_p} \quad (4.4)$$

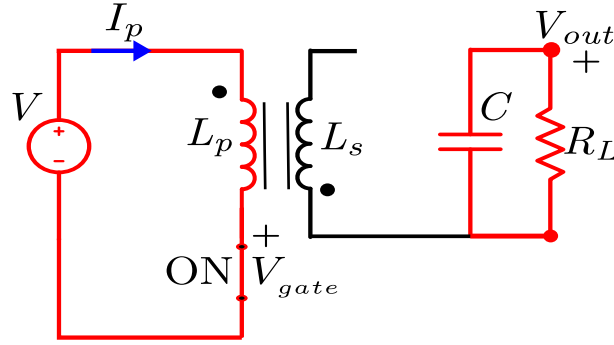


Fig. 4.2 Resultant Flyback converter circuit during the ON state.

The ON time period is expressed by:

$$t_{on} = D_{PWM} \times T \quad (4.5)$$

where:

T = The switching period.

The average input current during the ON state is expressed by:

$$I_{ave} = \frac{1}{T} \int_0^{t_{on}} I_p(t) dt \quad (4.6)$$

Since the current waveform of I_p is triangular in shape, see Figure 4.3, I_{ave} can be expressed by the area of a triangle and equation 4.6 reduces to:

$$I_{ave} = \frac{D_{PWM} \times I_{peak}}{2} \quad (4.7)$$

Substituting equation 4.4 and then equation 4.5 into equation 4.7 yields:

$$I_{ave} = \frac{V \times D_{PWM}^2 \times T}{2 \times L_p} \quad (4.8)$$

Using equation 4.8, the primary-side inductor current of a DCM Flyback converter can be reconstructed from knowledge of the voltage across the inductor, the primary-side inductance, PWM duty-cycle and switching period.

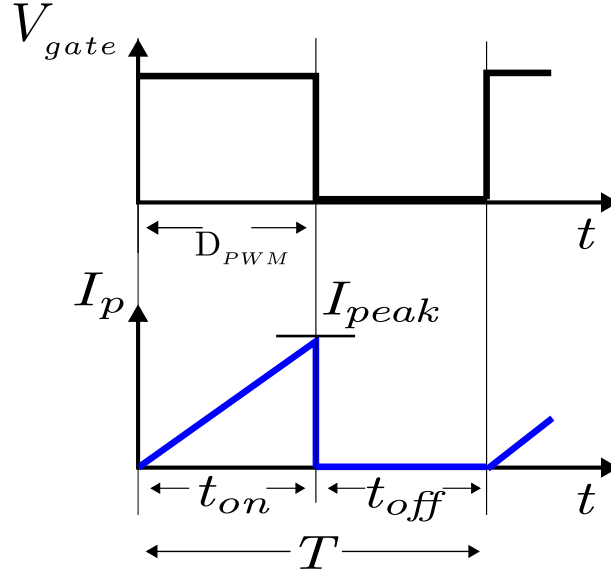


Fig. 4.3 Primary side current waveform of a DCM Flyback converter.

4.3 Model Validation Test

The model expressed by equation 4.8 was validated by comparing the accuracy of the model to the sense resistor technique. The primary-side inductor current of the Flyback converter developed in Chapter 3 was estimated by the model and sensed using a sense resistor R_{sense} . The circuit depicted by Figure 4.4 was constructed. A sandblock, ceramic, wire wound, $10\ \Omega$, $20\ \text{W}$ sense resistor was used for R_{sense} . A DC power supply, V_{DC} was connected to the input of the Flyback converter and set to $17.7\ \text{V}$ and current limited to $2.33\ \text{A}$ to ensure the rated power of the transformer, $P_{rated} = 40\ \text{W}$, was not exceeded. A $12\ \text{V}$ lead acid battery, V_{bat} was connected at the output of the Flyback converter to sink the output power and obviated the need for a variable load or voltage feedback to the control platform. Two signals were input to the control platform, the supply voltage v_{DC} and the voltage across R_{sense} , v_{sense} . Voltage dividers were used to scale down the input signals to the ADC input voltage range.

The process depicted by Figure 4.5 was modelled in software and uploaded to the MCU. D_{PWM} was stepped through in increments of 0.5% to increase the output power until P_{rated} was delivered. The maximum D_{PWM} was limited to $D_{max} = 48\%$. The primary-side inductor current calculated using the model is I_{model} . Current $I_{R_{sense}}$ is the current calculated using the sense resistor technique. The correlation coefficient between I_{model} and $I_{R_{sense}}$ was calculated using:

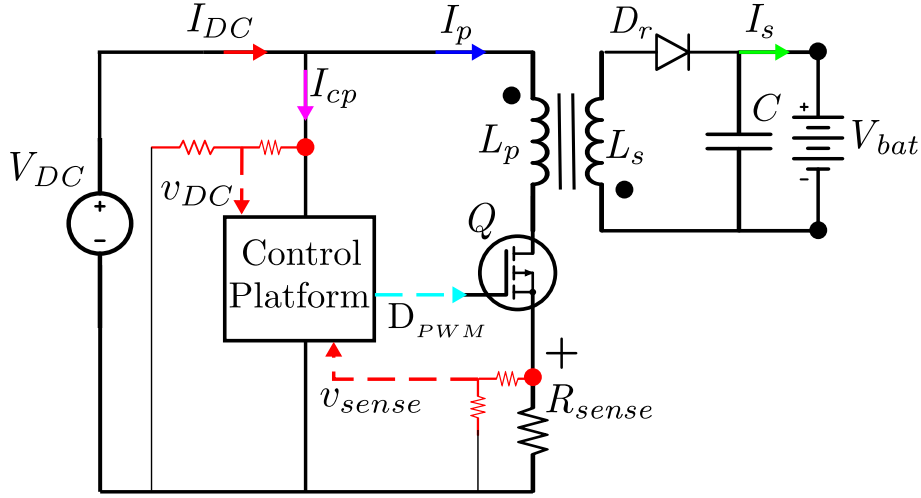


Fig. 4.4 Schematic of the circuit used for the model validation test.

$$r = \frac{COV(I_{R_{sense}}, I_{model})}{s_{I_{R_{sense}}} s_{I_{model}}} \quad (4.9)$$

where:

$COV(I_{R_{sense}}, I_{model})$ = The covariance of $I_{R_{sense}}$ and I_{model} .

$s_{I_{R_{sense}}}$ = The sample standard deviation of $I_{R_{sense}}$.

$s_{I_{model}}$ = The sample standard deviation of I_{model} .

The equations for calculating the covariance and the sample standard deviation are given in Appendix C.

4.3.1 Results

The model-based current is compared to the sensed current in Figure 4.6. The correlation coefficient between $I_{R_{sense}}$ and I_{model} was: $r = 0.9998$. The correlation coefficient between $I_{R_{sense}}$ and I_{model} above the rated power of R_{sense} (20 W) was: $r = 0.9974$.

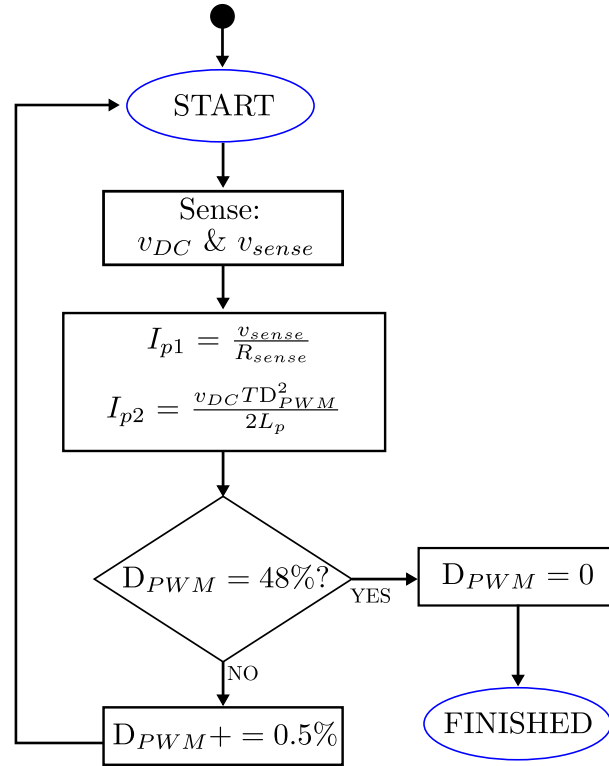


Fig. 4.5 UML diagram of the process executed on the control platform for the model validation test.

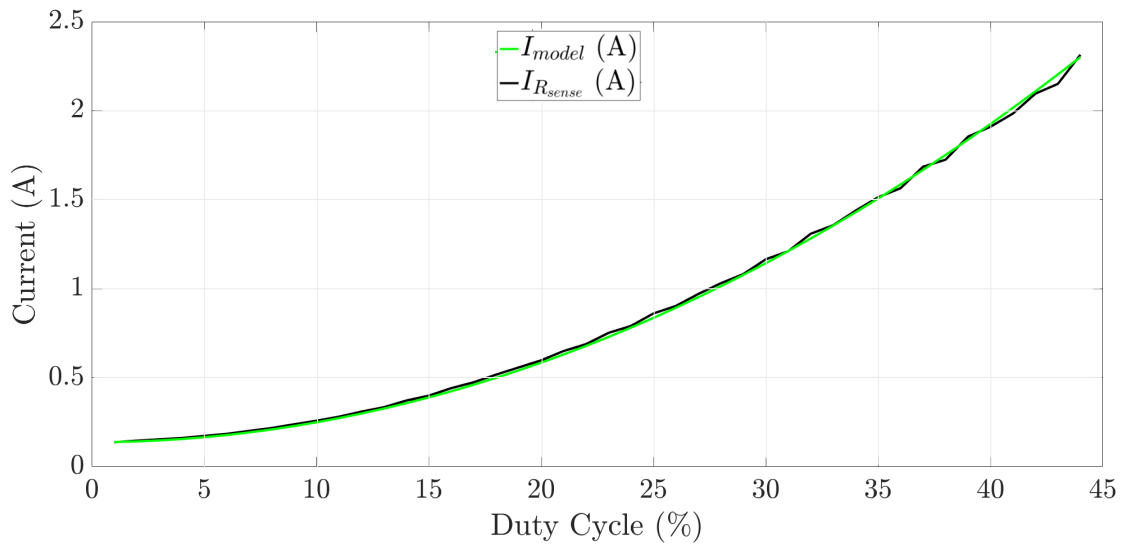


Fig. 4.6 Plot comparing the model-based current to the current sensed using a sense resistor.

4.3.2 Discussion

The strong correlation between $I_{R_{sense}}$ and I_{model} validates that equation 4.8 can accurately estimate the primary-side inductor current of a DCM Flyback converter. The model-based technique is deemed suitable for the application of model-based MPPT. The correlation coefficient was expected to reduce above the rated power of R_{sense} . R_{sense} varies with an increase in temperature above the rated power. This causes the accuracy of $I_{R_{sense}}$ to reduce. This can be overcome by using higher power resistor. However, compared to the model-based technique, this will increase cost and requires integration of R_{sense} into the board design. Furthermore, the model-based technique offers superior efficiency over the sense resistor technique. A drawback of the model-based technique is that the values of the parameters for equation 4.8 must be precisely known or the accuracy of the technique will suffer.

4.4 Concluding Remarks

The accomplishment of the fourth research objective was communicated in this Chapter. An equation was derived that models the primary-side inductor current of a DCM Flyback converter. The model-based technique accurately estimates current compared to the conventional sense resistor technique. The advantages of the model-based technique are that it is non-invasive and efficient. The drawback is that the values of the model parameters must be precisely known. The model-based technique is deemed suitable for the application of this research which is to perform model-based MPPT.

Chapter 5

Control Strategy at the Interface

The MCU opens the door to new opportunities for the design and execution of the stigmergic based control strategy as an embedded control solution. An overview of the control strategy was given in Chapter 2. Blocks comprising to the PeCo grid endeavour to keep the grid voltage, V_g sensed at their three-port connection within a stable region of operation bounded by a minimum and maximum voltage V_{min} and V_{max} . This is accomplished by approaching a nominal voltage V_{nom} which lays within the bounded range. The control action does not stabilise V_g at V_{nom} but fluctuates about V_{nom} . Fluctuation of V_g about V_{nom} is permitted to allow for the MCU to monitor events on the grid.

V_g is the single target variable that is shared amongst all blocks. The MCU will perform a control action based on V_g sensed. The control action regulates power flow from the element to the grid to ensure V_g remains within the stable region. Bus voltage signalling is used to communicate V_g to each block because the control architecture is decentralised and lacks a communications network. V_g is sensed at the three-port connection and fed back to the MCU.

Before the control strategy can be deployed on the MCU, a revision and an adaptation are required. In this Chapter the answer to the second research sub-question and the accomplishment of the fifth research objective is communicated.

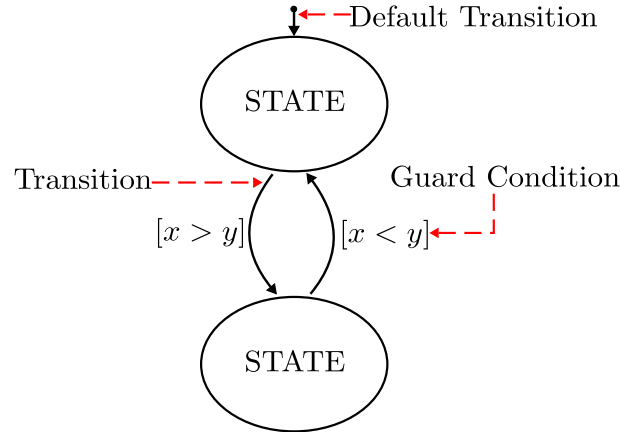


Fig. 5.1 Simple state diagram.

5.1 Finite State Machines

Finite state machine (FSM) concepts are used to model system behaviour where the output is dependent on the present input as well as the present state of the system. The basic operation of a FSM is to traverse through states where the future state is determined according to the present state and present input conditions. The FSM generates an output based on the present state and input conditions. This behaviour can be represented by a state diagram, see Figure 5.1. Ellipses represent states and arrows between states represent state transitions. When initiated, the FSM begins at the default transition. Guard conditions are Boolean-valued expressions displayed next to transition arrows which when evaluated to true, cause transitions between states. A FSM that generates an output within a state is called a Moore machine and a FSM that generates an output at transitions is called a Mealy machine.

Consider the basic operation of a GEN block. The power supplied to the grid, “the output”, is dependent on V_g , “the input”, and the present control action, “the state”, of the MCU. Based on this logic, the control strategy can be modelled using FSM concepts. Control actions can be represented by states and changes to V_g may initiate transitions between states causing the MCU to execute different control actions.

5.2 Embedded Control Strategy

A feature of the MCU that contributed to its selection for this research, was the unique software development environment and toolchain for embedded control solution design that it offered. The control strategy is adapted to be deployed on the MCU by modelling it as a state diagram in software. The software development environment generates the code for the state diagram model and uploads it to the MCU as an executable file. The control strategy was designed according to the stigmergic agent-based approach discussed in Chapter 2. As validated on the Legacy Grid, this will ensure that the following can be achieved:

- Autonomous commissioning and operation.
- Tolerance to faults without affecting the operation of other blocks.
- Coordinated control of power flow with other blocks interfaced to the grid.

5.2.1 Inputs Output and Rationale

Figure 5.2 depicts a block diagram model of the inputs to and the output from the state machine with the embedded control strategy modelled as a state diagram. This model was created in software. The ADC and PWM peripherals of the MCU were configured using blocks as opposed to written code. In the real world, the inputs to the ADC are the grid voltage and PV module voltage V_g and V_{pv} . In software, the ADC outputs signals v_g and v_{pv} . v_g and v_{pv} are converted to their real-world values, V_g and V_{pv} , by multiplying by a gain calculated from equation 5.1 before being input to the state machine.

$$k_{\text{ADC}} = \frac{V_{\text{ADC}_{\text{max}}}}{R_{\text{div}} \times 2^n} \quad (5.1)$$

where:

R_{div} = The voltage divider ratio of the resistors used to scale the real-world values to the input range of the ADC.

Inputting the real-world values to the state machine obviates the need to convert parameters to ADC bit values and simplifies the design of the control strategy. The

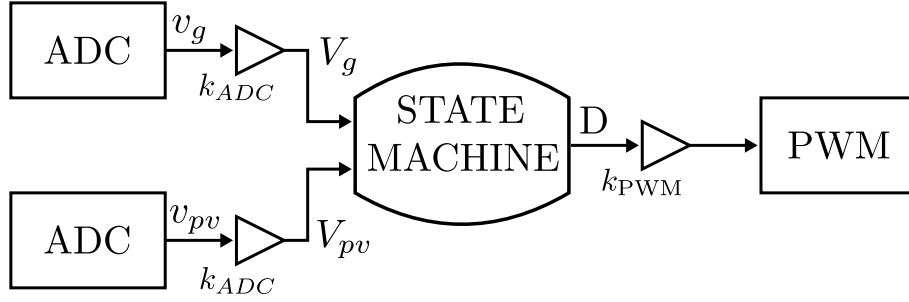


Fig. 5.2 Inputs from the ADC to the state machine and output to the PWM.

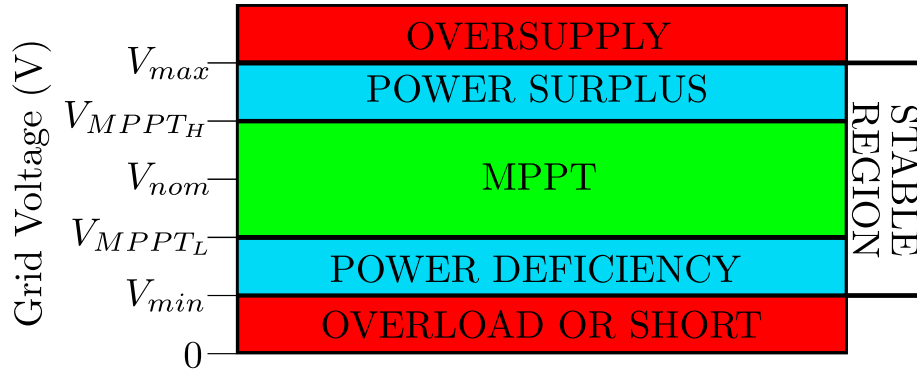


Fig. 5.3 Grid power status inferred from V_g .

D_{PWM} output from the state machine is the real-world value of the PWM duty-cycle. D_{PWM} is multiplied by gain k_{PWM} before being input to the PWM peripheral of the MCU. The PWM peripheral of the MCU uses a counter compare module where a counter value represents a scaled equivalent of the output D_{PWM} . D_{PWM} is scaled by k_{PWM} to be input as a counter value.

The power status of the grid is inferred from V_g , see Figure 5.3. The primary control objective is to keep V_g within the stable region bounded by V_{min} and V_{max} . The MCU continuously senses V_g to infer the grids power status and inputs V_g to the state machine. Transitions between states are made based on the power status of the grid inferred from V_g .

The secondary control objective is to perform MPPT. When V_g is fluctuating about V_{nom} within the region bounded by V_{MPPTL} and V_{MPPTH} , MPPT is performed. V_{pv} is input to the state machine as a required parameter for the MPPT algorithm discussed in Chapter 6. The single output from the state machine is D_{PWM} . When the grids power status changes, V_g will fluctuate. The control will respond to the fluctuation by increasing or curtailing the power from the element by adjusting D_{PWM} .

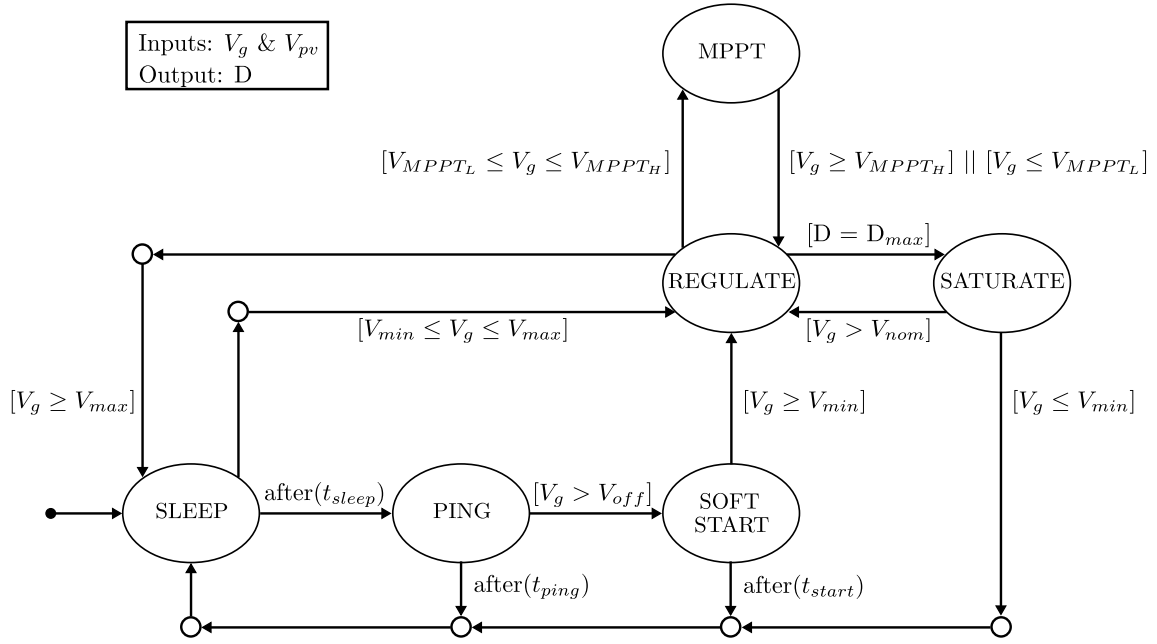


Fig. 5.4 State diagram model of the embedded control strategy.

5.2.2 State Diagram

Figure 5.4 depicts the state diagram model of the embedded control strategy. Each state represents a different control action. Upon commission, a block can be faced with two possible scenarios. The first scenario is a black start. Black start occurs when there is no existing grid to connect to or the grid has shut down due to a fault condition. The second scenario is to connect to an existing grid that is operating within the stable region. When faced with the second scenario, a block must connect to the grid and commission in a coordinated and shared manner with other blocks on the grid and ensure V_g remains in the stable region.

SLEEP

Upon commissioning, the default transition is to the SLEEP state. The control action state sets $D_{PWM} = 0$. From this state, the MCU can establish which scenario it is presented with. If black starting, $V_{min} \leq V_g \leq V_{max}$ will evaluate to false and after a set time period t_{sleep} , the state machine transitions into the PING state. If connecting to a stable grid, $V_{min} \leq V_g \leq V_{max}$ will evaluate to true and the state machine will transition into the REGULATE state.

The SLEEP state is transitioned into from the REGULATE state or the SATURATE state when the primary control objective cannot be met and the grids power status is either an oversupply or overload. An oversupply will raise V_g until $V_g \geq V_{max}$ evaluates to true. An overload will reduce V_g until $V_g \leq V_{min}$ evaluates to true. During time period t_{sleep} the block is off. This time period allows for the end-user to safely modify the grid architecture while the block is off to achieve a configuration that will result in stable grid operation.

PING

The PING state is transitioned into from the SLEEP state after the set time period t_{sleep} has elapsed. The control action within the PING state pings the grid by alternating between holding D_{PWM} at a constant value D_{ping} and 0. This control action sends out a current pulse from the block which attempts to raise V_g above an off voltage, V_{off} . The PING state serves as a short-circuit protection state.

In the event of a short-circuit fault, $V_g \geq V_{off}$ will evaluate to false because the short-circuit prevents any increase in V_g . The block will continuously ping the grid until the fault is removed or the time period t_{ping} has elapsed. If t_{ping} has elapsed, the state machine transitions to the SLEEP state.

In the event that there is no short-circuit fault on the grid, the current pulse will raise V_g and $V_g \geq V_{off}$ will evaluate to true. The state machine will transition from the PING state into the SOFT START state. In the event of there being multiple blocks pinging the grid, the sum of their current pulses will contribute to raising V_g .

SOFT START

If through the pinging effort of a single or multiple blocks, $V_g \geq V_{off}$ evaluates to true, the state machine transitions into the SOFT START state. The control action within the SOFT START state ramps up V_g until $V_g \geq V_{min}$ evaluates to true and the grid is operating in the stable region. This is accomplished by increasing the output current of the block and monitoring the response of V_g . A proportional control scheme is used. The change in output ΔD_{PWM} is proportionally controlled according to the difference between the set-point V_{min} and the process variable V_g , see equation 5.2.

$$\Delta D_{PWM} = k_p(V_{min} - V_g) \quad (5.2)$$

where:

k_p = The proportional control coefficient.

After calculating ΔD_{PWM} , the current output of the block is adjusted according to:

$$D_{PWM_{n+1}} = D_{PWM_n} + \Delta D_{PWM} \quad (5.3)$$

If $V_g \geq V_{min}$ evaluates to true, the state machine transitions into the REGULATE state. This indicates that the black start was successful. If the time period t_{soft} expires, the state machine transitions into the SLEEP state. This indicates an overload on the grid and an unsuccessful black start. The end-user must either scale the grid power capability up by adding more GEN or ES blocks or remove some of the load. The SOFT START state permits for a soft start raising of V_g during a black start to avoid V_g overshooting the stable region.

Multiple blocks can sync their efforts to black start a grid and share the load demand. For example, if the load demand on the grid is double the power capability of a block, the block cannot black start the grid. If a second block with equal power capability is connected to the grid, both blocks will black start the grid and share the load demand. This example highlights the power solubility feature of the PeCo grid. By simply plugging in an extra block, the end-user has scaled up the grid power by 100%.

REGULATE

The REGULATE state is transitioned into after a successful black start or if a block is connected to an existing grid operating within the stable region and $V_{min} \leq V_g \leq V_{max}$ evaluates to true. The control action within the REGULATE state controls D_{PWM} according to the proportional control scheme expressed by Equation (5.2) with the set-point changed from V_{min} to V_{nom} . In the event of there being a load added or removed from the grid whilst V_g is within the stable region, the control action within the REGULATE state is tasked with preventing V_g raising above or falling below the stable region by decreasing or increasing D_{PWM} respectively. The shortcoming of the

Legacy Grid was that drastic and sustained increases in V_g above the stable region were observed during load removal. The control action within the REGULATE state aims to overcome this.

In the event that V_g is within the stable region and $V_{MPPT_L} \leq V_g \leq V_{MPPT_H}$ evaluates to true, the state machine transitions from the REGULATE state into the MPPT state. This indicates that the fluctuation of V_g about V_{nom} is minor and MPPT can be performed.

In the event that the grid load demand is greater than the maximum supply from the block, V_g will decrease below V_{nom} . The control action responds by increasing D_{PWM} until $D_{PWM} = D_{max}$. When $D_{PWM} = D_{max}$ evaluates to true, the state machine transitions from the REGULATE state into the SATURATE state.

SATURATE

The SATURATE state is transitioned into when the power limit of the block set by D_{max} is reached. Whilst in the SATURATE state the grid operates within the power deficiency region. The control action within the SATURATE state does nothing. The state machine transitions from the SATURATE state into the SLEEP state if the load demand is increased above the blocks power capability causing $V_g \leq V_{min}$ to evaluate to true.

The state machine will transition from the SATURATE state into the REGULATE state if the load demand is reduced or if the grid power is scaled up by connecting more blocks. The reduction in load or increase in supply will cause an increase in V_g until $V_g > V_{nom}$ evaluates to true. The SATURATE state serves as an indication that the load demand is too high and the block is operating at maximum power output.

MPPT

When $V_{MPPT_L} \leq V_g \leq V_{MPPT_H}$ evaluates to true, the state machine transitions into the MPPT state from the REGULATE state. The control action within the MPPT state performs MPPT. Maximum power can only be delivered from the PV module if there is sufficient load on the grid to accept it. For example, if an ES block with a depleted battery is connected to the grid. The maximum power can be delivered from

the PV module to the grid and the ES block will sink excess power not drawn by the loads for battery charging.

Maximum power cannot be delivered if there isn't sufficient load or an ES block with a depleted battery connected to the grid. Under this scenario, if the maximum power point delivers more power than the load demand, V_g will increase to indicate a power surplus on the grid. $V_g \geq V_{MPPT_H}$ will evaluate to true, The state machine will transition into the REGULATE state and V_g will be decreased.

A change in load demand whilst the grid is operating within the MPPT region will cause a change in V_g and $V_g \geq V_{MPPT_H}$ or $V_g \leq V_{MPPT_L}$ may evaluate to true. This will cause the state machine to transition from the MPPT state into the REGULATE state. The MPPT state is covered in further detail in Chapter 6.

5.3 Control Strategy Testing

Tests were conducted to validate if the control strategy could meet the goals laid out in Section 5.2 and to establish the following:

- The response of V_g and the control action during a black start.
- The response to and ability to tolerate a short-circuit fault or overload.
- The response of V_g and the control action when connecting a block to an existing grid.
- The response of V_g and the control action when changes in load on the grid are made.

Testing of the MPPT state is covered in Chapter 6.

5.3.1 Test Set-up

The parameters of the state diagram that were set for conducting all tests are listed in Table 5.1. The PeCo grid depicted by Figure 5.5 was built. A real-world picture of the test set-up is depicted by Figure 5.6. Each of the tests conducted in the following

Table 5.1 Test parameters.

Parameter	Value
P_{mpp}	30 W
P_{max}	22.5 W
I_{max}	1.8 A
I_{mpp}	1.77 A
V_{mpp}	17.2 V
V_{nom}	12.5 V
V_{min}	10 V
V_{max}	14 V
V_{off}	0.5 V
t_{sleep}	0.5 s
t_{ping}	1 s
t_{start}	0.2 s
D_{max}	48%
D_{ping}	1%

sections was conducted under two conditions. The first being using one block to establish the control response of a single block and the second being using two blocks to establish the cooperative control response.

DC power supplies were interfaced to the grid and used to emulate a PV module element. This ensured the repeatability of test conditions. The DC supply voltage was set to V_{mpp} and the output current limited to I_{mpp} which limited the output power to P_{mpp} . The efficiency of the Flyback at P_{mpp} was calculated in Chapter 3 to be $\eta = 75\%$. The maximum output power and output current of a block at P_{mpp} are P_{max} and I_{max} and are listed in Table 5.1.

The loads connected to the grid are dumb loads controlled by manually operated switches. The loads connected to the test grid were: two 12 V, 5 W LED bulbs (B_1 and B_2) and two variable resistors (R_1 and R_2). R_1 and R_2 were manually varied to adjust the load current on the grid I_L . During testing B_1 and B_2 provide visual feedback to changes in I_L . Voltage and current measurements were taken using the Tektronix MDO304 oscilloscope. Variables that were measured are: V_g , the output current from each block I_A and I_B and I_L . $I_L = I_A$ for tests conducted with a single block and $I_L = I_A + I_B$ for tests conducted with two blocks.

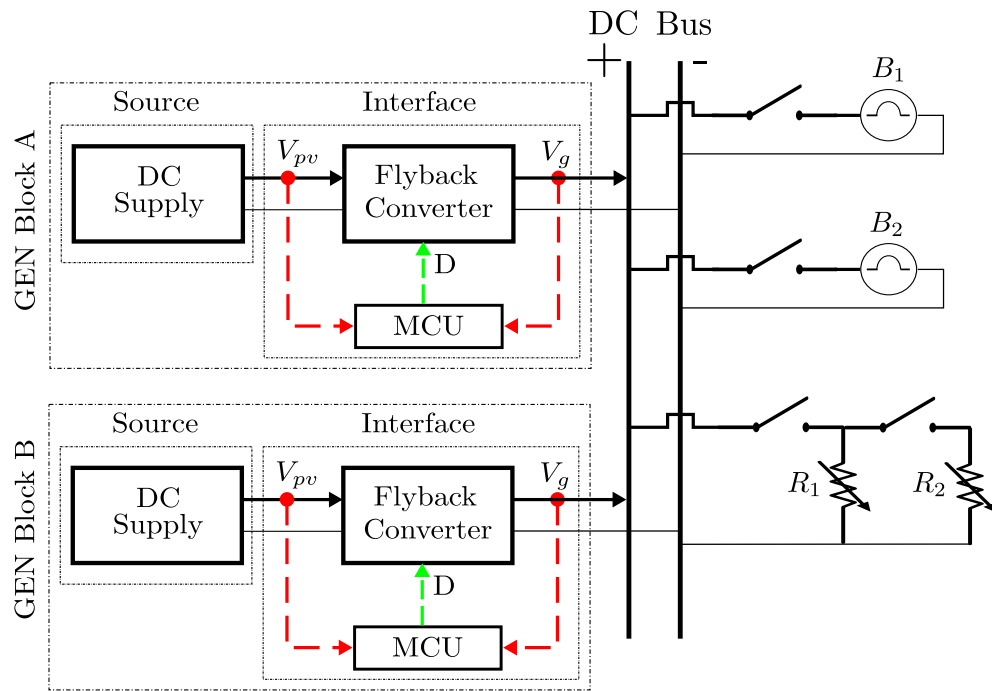


Fig. 5.5 Schematic representation of the test PeCo grid.

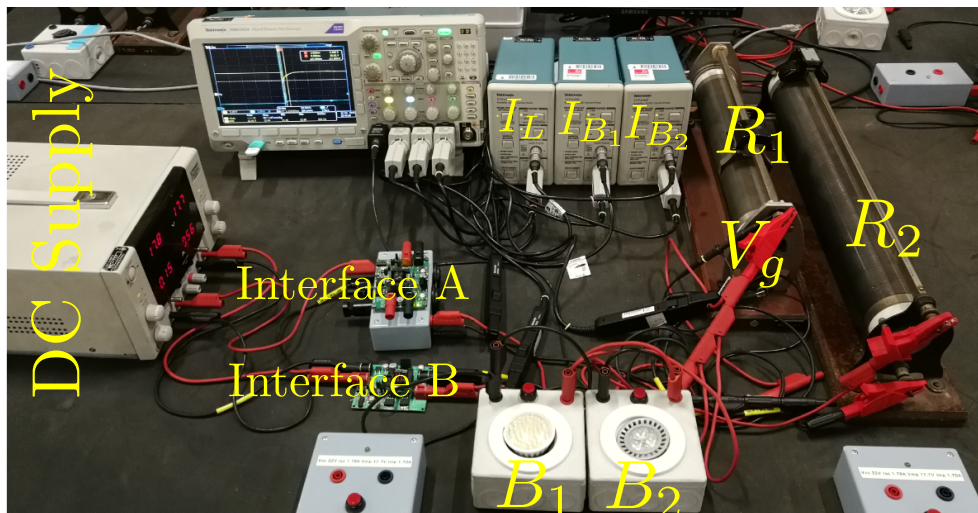


Fig. 5.6 Real-world picture of the test PeCo grid.

Table 5.2 Time taken to black start.

Case	$t_{P_{max}}$
Single block black start	112 ms
Cooperative black start	120 ms

5.4 Black Start Test

This test was conducted to establish the control response during a black start and to tune k_{soft} . The control of a single block and the cooperative control of two blocks to black start a grid up to P_{max} was tested. R_1 and R_2 were set to draw P_{max} for the single block case and $2 \times P_{max}$ for the cooperative case.

A black start up to P_{max} is the most drastic black start case that a block can be faced with. If the block can successfully black start up to P_{max} , then a valid assumption would be that for black start cases where the load is $\leq P_{max}$, black start will be successful. A black start is considered successful if the control action within the SOFT START state can raise V_g into the stable region without overshooting V_{nom} . The time taken to black start the grid up to P_{max} , $t_{P_{max}}$, was measured.

5.4.1 Results

Results of $t_{P_{max}}$ are presented in Table 5.2. The control response to a black start is plotted in Figure 5.7 and Figure 5.8 for the single block and cooperative cases respectively. At A, black start initiates. At B, $V_g \geq V_{min}$ evaluates to true. The state machine transitions into REGULATE. From B-C the control action increases D_{PWM} and keeps V_g in the stable region.

5.4.2 Discussion

The control response to a black start was established. The control of a single block and cooperative control of two blocks successfully black started the grid up to P_{max} . Test results validate that the grid power can be scaled up by adding a block and the blocks on the grid will share the load demand in an autonomous manner.

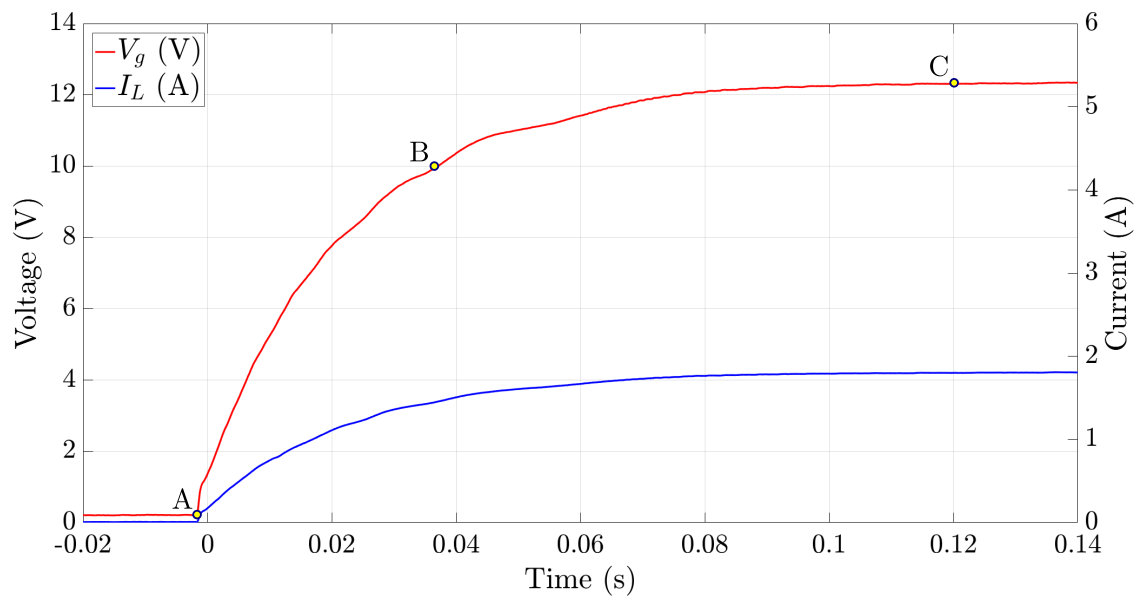


Fig. 5.7 Single block black start.

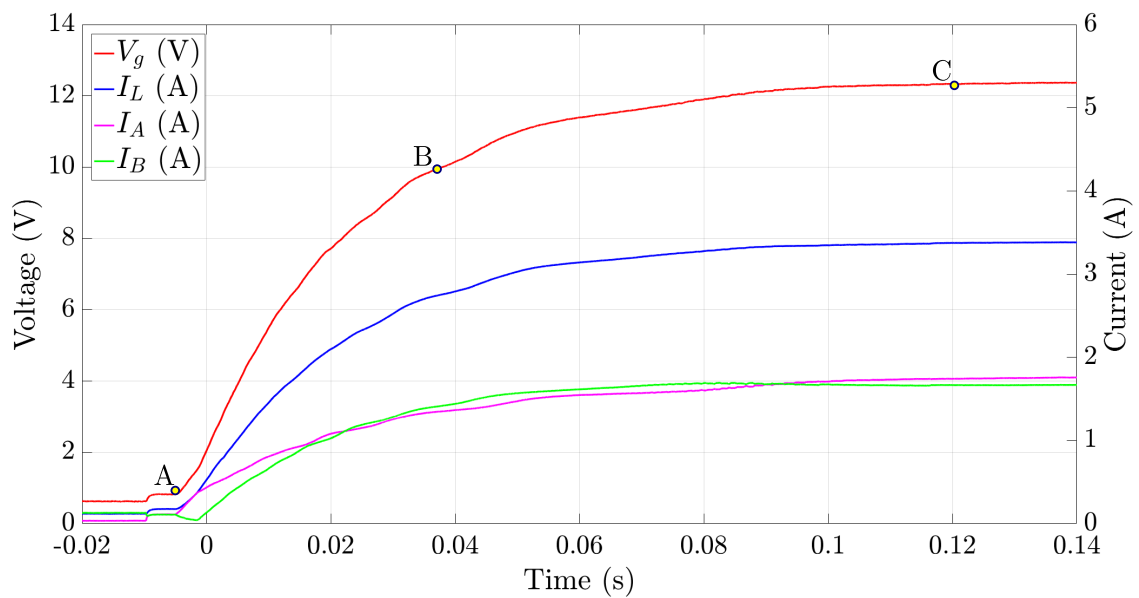


Fig. 5.8 Cooperative black start.

k_{soft} was manually tuned by an iterative process of setting a value of k_{soft} , observing the black start response and then making an appropriate adjustment to k_{soft} . k_{soft} was tuned to achieve the fastest possible black start time without V_g overshooting V_{nom} . k_{soft} was tuned to $k_{soft} = 5 \times 10^{-5}$. The time taken to black start can be sped up by increasing k_{soft} at the expense of control precision which may cause V_g to overshoot V_{nom} .

5.5 Short-circuit Protection Test

This test was conducted to establish the following:

- The control response to a short-circuit fault.
- If the control action within the PING state can protect a block from a persistent fault.
- If the block can recover from the fault and restore the grid to the operating conditions prior to the fault being applied after the fault is removed.

The grid was black started and loads varied until P_{max} was drawn. Following this, a short-circuit fault was applied to the DC bus. The fault is applied under P_{max} conditions to validate that the block can survive and restore from being shorted whilst delivering maximum power to the grid.

5.5.1 Results

The control response to a short-circuit fault is plotted in Figure 5.9 and Figure 5.10 for the single block and cooperative test cases respectively. Before A, P_{max} is supplied to the grid and V_g is within the stable region. At A, the fault is applied. V_g , I_A and I_B drop to 0.

When the fault is applied, the control action within the REGULATE state responds to the decrease in V_g by increasing D_{PWM} until D_{max} in an attempt to keep V_g in the stable region. This is observed by the transient spike of all currents when the fault is applied. The state machine transitions to the SATURATE state when $D_{PWM} = D_{max}$ evaluates to true. The control action halts any further increase in D_{PWM} .

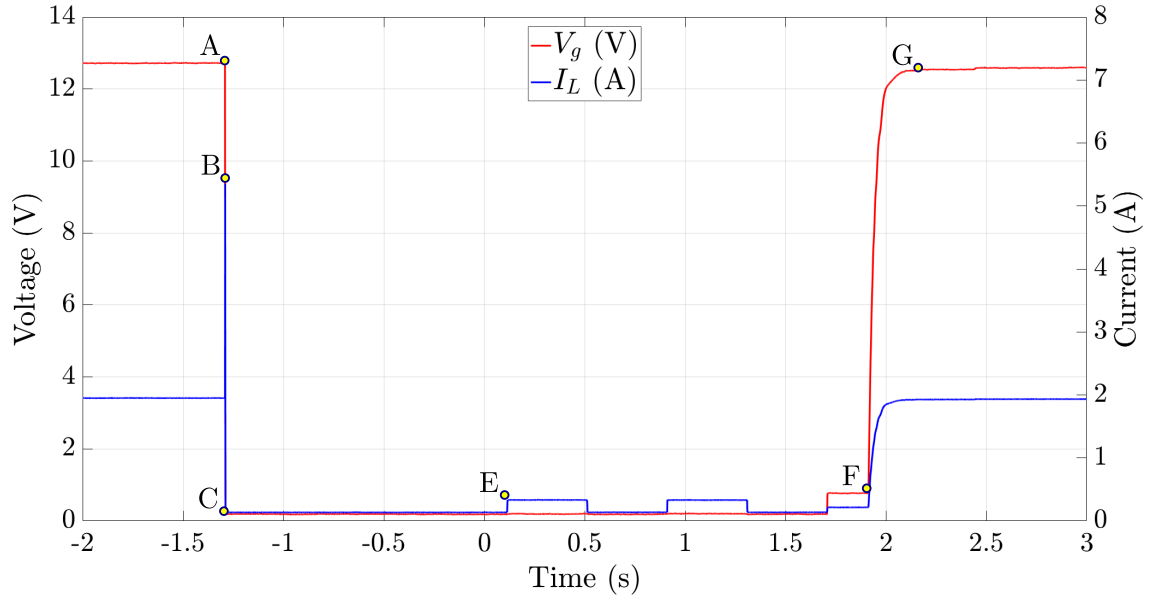


Fig. 5.9 Single block overload and short-circuit.

From A-C, V_g plummets until $V_g \leq V_{min}$ evaluates to true. The state machine transitions to the SLEEP state and sets $D_{PWM} = 0$. The time taken for a block to respond to the fault and enter the SLEEP state was 2 ms.

From A-E, the grid is shut down and the state machine is in the SLEEP state. At E, t_{sleep} has elapsed. The state machine transitions to the PING state. The control action sends out a current pulse to the grid at E. From E-F, the state machine is in the PING state and can be observed to be pinging the grid in an attempt to raise V_g above V_{off} . In Figure 5.10, the sum of I_A and I_B depicted by I_L contributes to raising V_g . However, from E-F, $V_g \geq V_{off}$ continues to evaluate to false as the fault is persisting. At F, the fault is removed and the grid is back started.

5.5.2 Discussion

The control response of the MCU to a short-circuit fault was established. The state machine transitioned to the SLEEP state when the fault was applied. The PING state control action protected the block from the persistent fault. The blocks were able to recover from the fault and restore the grid to the operating conditions before the fault was applied. Blocks tolerated the fault in an autonomous and decentralised manner.

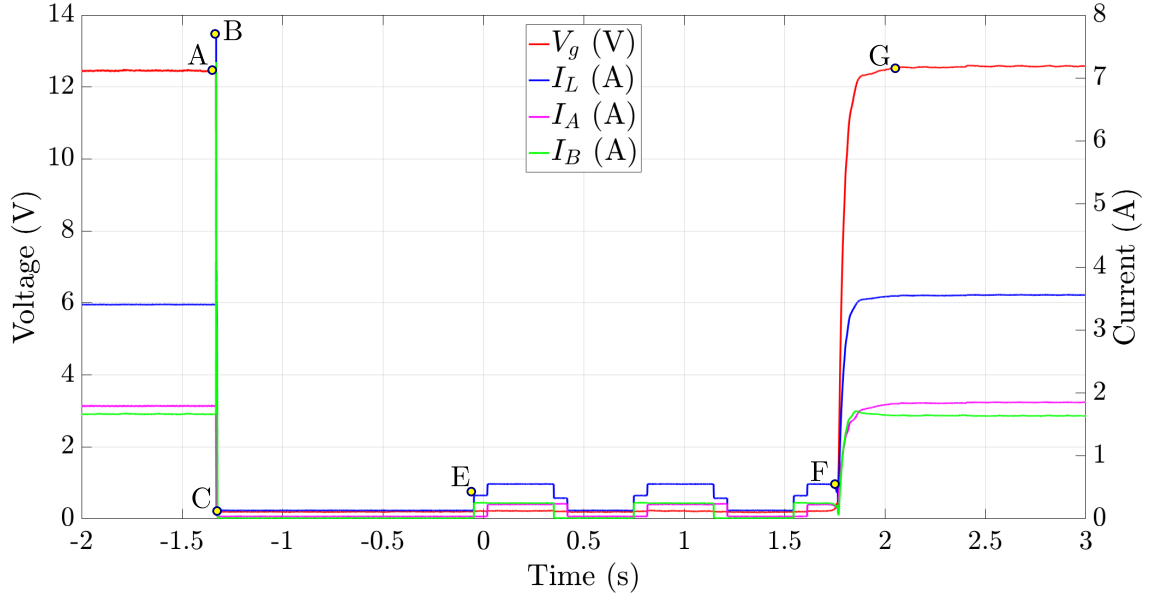


Fig. 5.10 Cooperative overload and short-circuit.

Each block attempted to black start the grid without knowledge of the other block status. The cooperation of multiple blocks pinging the grid was observed.

5.6 Connecting to an Existing Grid Test

This test was conducted to establish the control response when a block is connected to an existing grid operating in the stable region and to establish if and how the blocks will share the load. This is the second scenario that a block can be presented with as discussed in Section 5.2.2. The grid was black started by block A up to P_{max} and block B was connected to the DC bus.

5.6.1 Results

The control response to connecting a block to an existing grid is plotted in Figure 5.11. Before A, block B represented by I_B , is off and is in the SLEEP state. Block A represented by I_A is supplying P_{max} to the grid.

At A, block B is connected to the grid. For block B, $V_{min} \leq V_g \leq V_{max}$ evaluates to true and the state machine transitions from the SLEEP state into the REGULATE

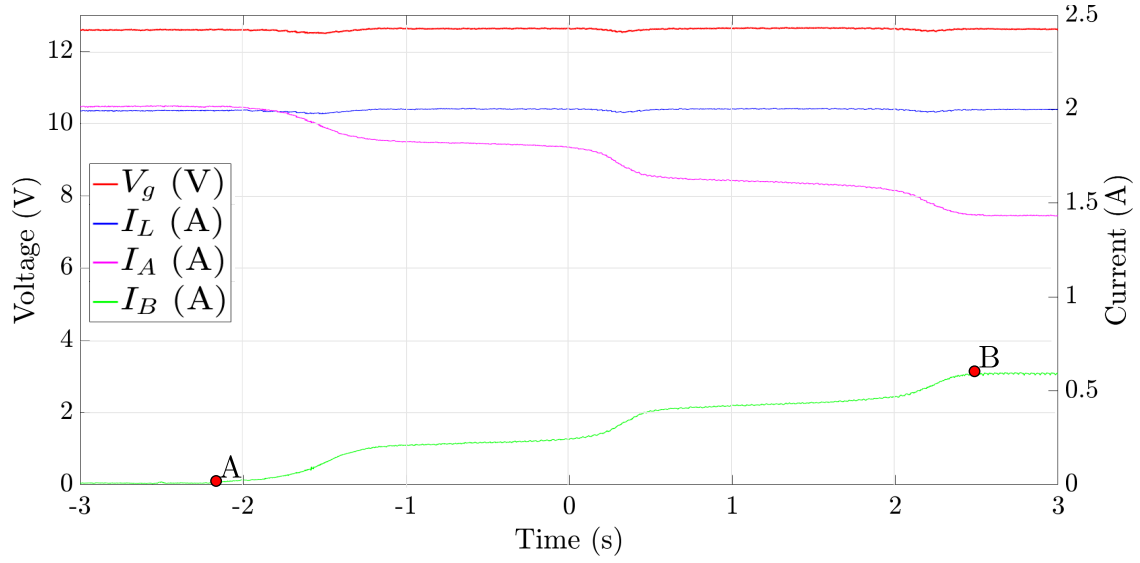


Fig. 5.11 Response to connecting a block to an existing grid.

state. From A-B, no change in I_L or V_g is observed which shows that connecting block B does not affect the grid's operation. Instead, I_A decreases and I_B increases as block B begins to inject current into the grid and share the load demand with block A. Block B does this in an autonomous and coordinated manner with block A so as to not cause any perturbations to V_g . The load is not equally shared between the blocks at B after which no further changes are observed.

5.6.2 Discussion

There is no load sharing control strategy in place and the autonomous nature of the blocks makes it difficult to establish how blocks share the load on the grid. However, test results show that load sharing between blocks does occur. The load does not have to be equally distributed between blocks for the grid to remain within the stable region.

5.7 Loading Test

This test was conducted to establish the control response to a loading event on the grid. Whilst the grid was operating within the stable region, I_L was stepped up by

connecting a load to the DC bus. Tests were conducted for the single block and the cooperative drastic cases and for several general cases of loading.

A drastic case of loading occurs when a block's output current is stepped up from no-load current, I_{NL} to full-load current, I_{max} . This is the largest step increase in block current that can occur when a load is connected to the grid hence the term drastic. Test conditions were set to emulate the drastic case. Blocks were connected to the DC bus and no loads were connected. The grid was black started and blocks delivered I_{NL} . Loads R_1 and R_2 were set to draw I_{max} and connected to the DC bus.

Loading cases other than the drastic case are considered general cases. Test conditions were set to emulate several general cases. Blocks and loads R_1 , B_1 and B_2 were connected to the DC bus. The grid was black started. R_1 was adjusted to set I_L to an initial load condition. I_L was then stepped up to an end load condition, I_{end} by connecting R_2 to the DC bus. The visual response of B_1 and B_2 to ΔI_L was observed.

5.7.1 Drastic Case Results

The results of the single block and cooperative control response to a drastic case of loading are plotted in Figure 5.12 and Figure 5.13. Before A, blocks output I_{NL} . At A, the load is connected. From A-C, V_g decreases and undershoots V_{nom} by V_{under} at C. The transient voltage undershoot occurs due to the instantaneous power draw when the load is connected which discharges the output capacitors of the Flyback converter.

The control responds to the decrease in V_g by increasing D_{PWM} which steps up I_L to I_{peak} at B. Despite the control action effort to increase D_{PWM} and I_L , I_L decreases from B-E and undershoots I_{max} by I_{under} at E. The transient current undershoot occurs because the output capacitors of the Flyback converter are recharging. At E the output capacitors have recharged.

From C-F, V_g is increased into the stable region indicating the end of the loading event. The measured results and settling time of the system, t_{settle} are presented in Table 5.3.

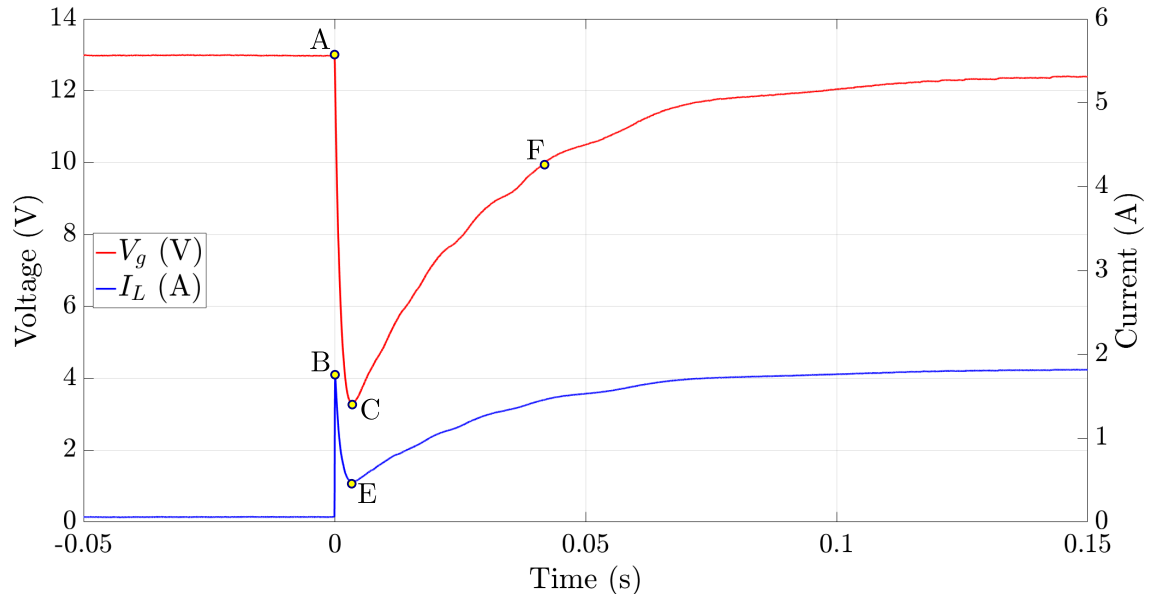
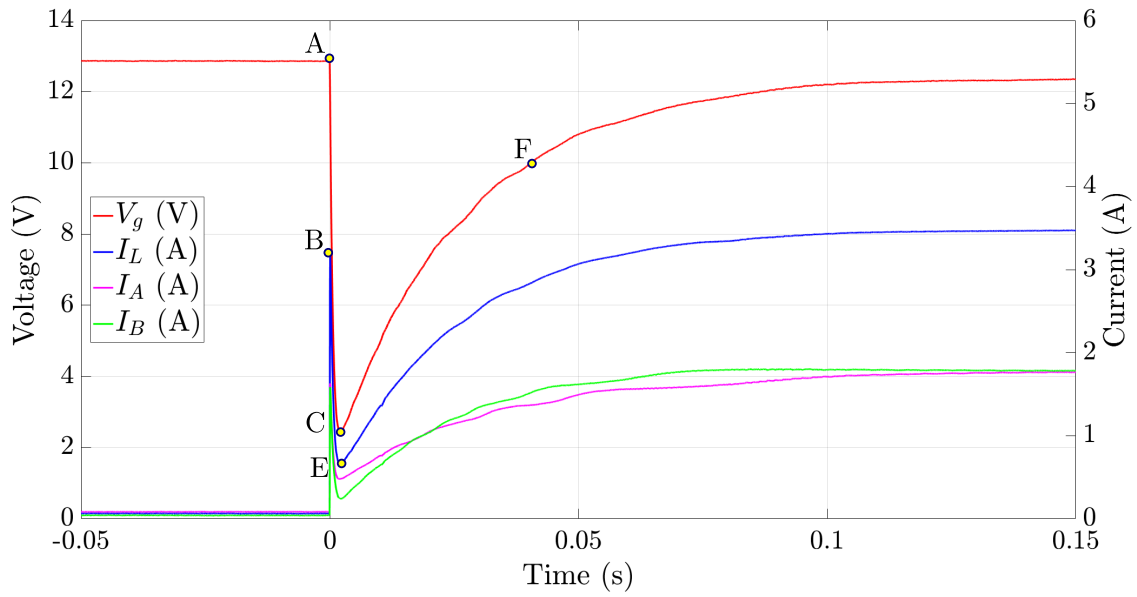
Fig. 5.12 Single block response to I_{NL} to I_{max} step.Fig. 5.13 Cooperative response to I_{NL} to I_{max} step.

Table 5.3 Response to drastic loading event.

$I_{NL} \rightarrow I_{max}$ (A)	ΔI_L (A)	V_{under} (V)	I_{peak} (A)	I_{under} (A)	t_{settle} (ms)
$0 \rightarrow 1.8$	1.8	3.3	1.7	0.5	176
$0 \rightarrow 3.5$	3.5	2.4	3.2	0.6	213

Table 5.4 Response to general loading events.

$I_i \rightarrow I_e$ (A)	ΔI_L (A)	V_{under} (V)	I_{peak} (A)	I_{under} (A)	t_{settle} (ms)
0.5 $\rightarrow$ 1	0.5	9	1	0.8	66
1 $\rightarrow$ 1.5	0.5	10.5	1.5	1.3	63
1.5 $\rightarrow$ 2	0.5	11.1	1.9	1.9	61
2 $\rightarrow$ 2.5	0.5	11.5	2.5	2.3	58
1 $\rightarrow$ 1.5	1	9	1.4	1.3	78
1.5 $\rightarrow$ 2	1	9.9	2.4	2	74
2 $\rightarrow$ 3	1	10.4	3	2.6	72
0.5 $\rightarrow$ 2	1.5	6.3	1.9	1	89
1.5 $\rightarrow$ 3	1.5	8.9	2.8	2.1	85
1 $\rightarrow$ 3	2	7.4	2.8	1.8	117
0.5 $\rightarrow$ 3	2.5	5.1	2.7	1.2	130

5.7.2 General Case Results

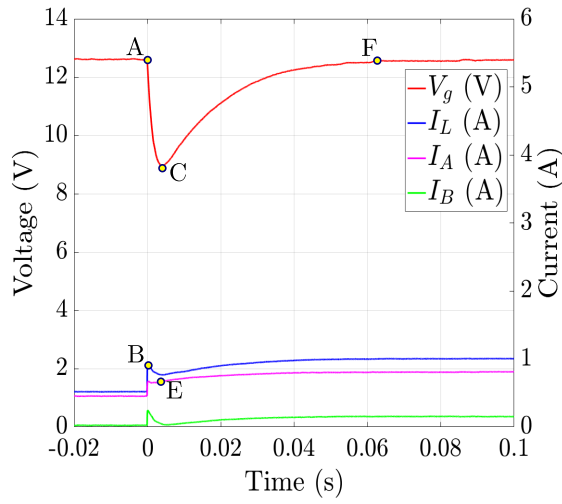
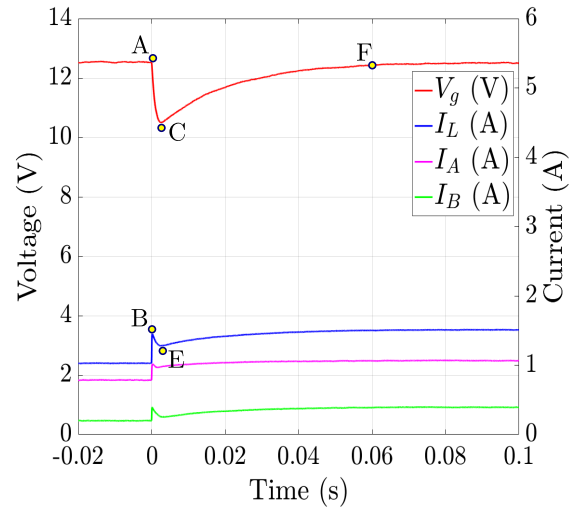
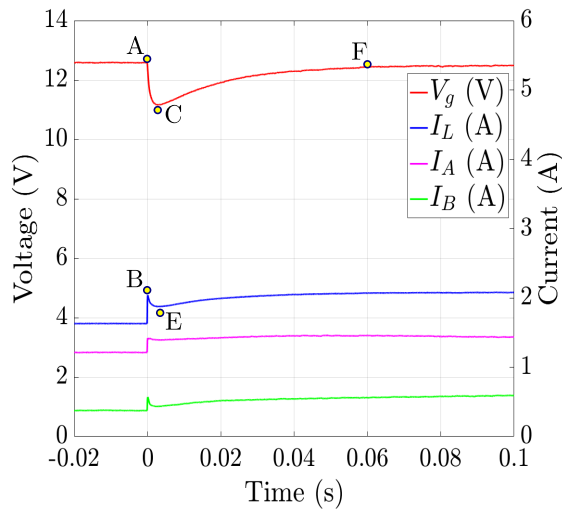
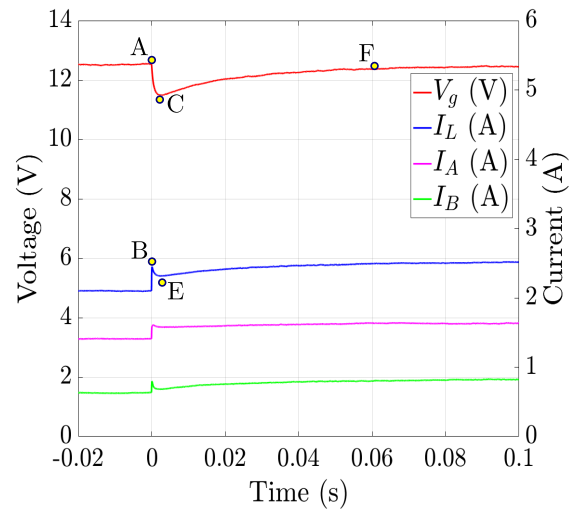
The control response to four general loading events with $\Delta I_L = 0.5$ A are plotted in Figures 5.14 to 5.17. The results of these specific cases are presented to highlight the variable response of V_g with constant ΔI_L and varying I_i test parameters. A plot of results for each, of all the general loading cases tested, are presented in Appendix D.

Before A, blocks are outputting $I_{initial}$. At A, the load is connected. From A-C, V_g decreases and undershoots V_{nom} by V_{under} at C. The control responds to the decrease in V_g by increasing D_{PWM} which steps up I_L to I_{peak} at B. From B-E, I_L decreases and undershoots I_{end} by I_{under} at E. From C-F, V_g is increased until $V_g = V_{nom}$ indicating the end of the loading event.

The measured results and settling time of the system, t_{settle} are presented in Table 5.4. When a load was connected to the DC bus a transient flickering effect was observed on $B1$ and $B2$.

5.7.3 Discussion

The control response of the MCU to a loading event was established. A decrease in V_g was observed when a load was connected to the grid due to the instantaneous power drawn by the load. This instantaneous power draw discharges the output capacitors of

Fig. 5.14 Step 0.5 A $\rightarrow$ 1 A.Fig. 5.15 Step 1 A $\rightarrow$ 1.5 A.Fig. 5.16 Step 1.5 A $\rightarrow$ 2 A.Fig. 5.17 Step 2 A $\rightarrow$ 2.5 A .

the Flyback converter and causes a transient undersupply to the grid. Results show that $\Delta I_L \propto V_{\text{under}}$. This means that the larger the load connected to the grid, the greater the undersupply and thus the greater the magnitude of the decrease of V_g . Results show that $\Delta I_L \propto t_{\text{settle}}$. This means the system takes longer to settle when large loads are connected to the grid.

All blocks connected to the grid should endeavour to keep V_g within the stable region during loading. For the tests conducted, the conditions were such that manually operated dumb loads were connected to the grid using a switch. Stepping the load into the grid in this manner caused V_g to undershoot out of the stable region. If a load interface was used to connect loads, the control at the interface can soft start the load. This will prevent the load from being stepped into the grid and V_g can be kept within the stable region. A recommendation for future research is to develop an interface for connecting a load to the grid in a soft start manner.

5.8 Load Removal Test

This test was conducted to establish the control response to a load removal event on the grid. Whilst the grid was operating within the stable region, I_L was stepped down by disconnecting a load from the DC bus. Tests were conducted for the single block and cooperative drastic cases and for several general cases of load removal.

A drastic case of load removal occurs when a block's output current is stepped down from full-load current, I_{max} to no-load current, I_{NL} . This is the largest step decrease in block current that can occur when a load is removed from the grid hence the term drastic. Test conditions were set to emulate the drastic case. The grid was black started and load conditions set to draw I_{max} . The load was then disconnected from the grid.

Load removal cases other than the drastic case are considered general cases. Test conditions were set to emulate several general cases. The grid was black started with all loads connected. Load conditions set to draw an initial current I_{initial} . I_L was then stepped down to an end load condition, I_{end} by disconnecting R_2 from the DC bus. The visual response of B_1 and B_2 to ΔI_L was observed.

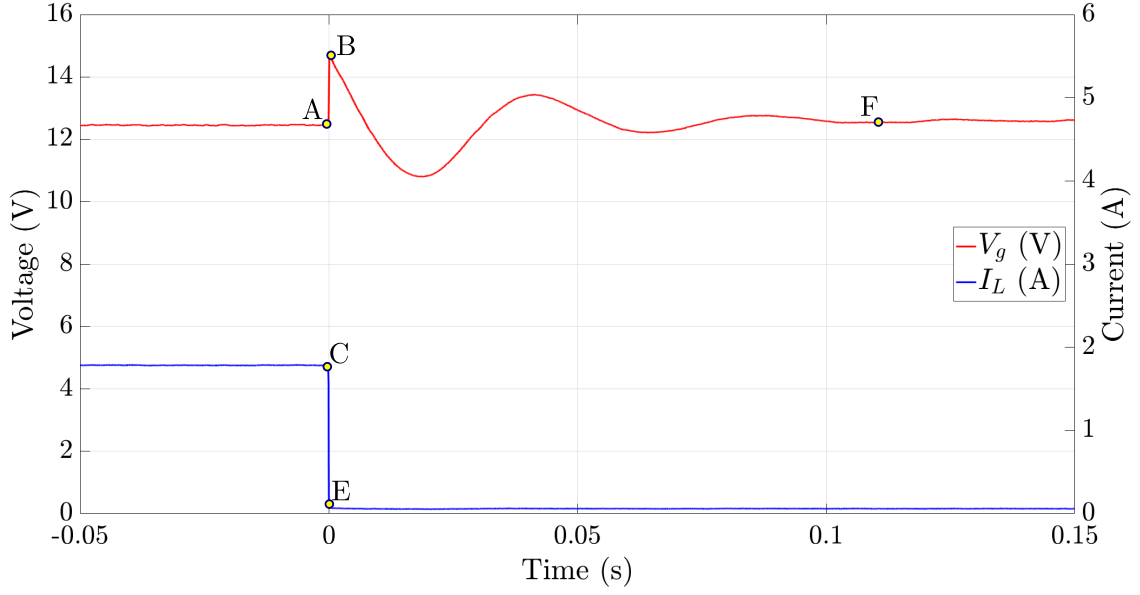
Fig. 5.18 Single block response to I_{max} to I_{NL} step.

Table 5.5 Response to drastic load removal event.

$I_{max} \rightarrow I_{NL}$ (A)	ΔI_L (A)	V_{peak} (V)	t_{settle} (ms)	t_{over} (ms)
1.8 $\rightarrow$ 0	1.8	14.8	102	2.4
3.6 $\rightarrow$ 0	3.6	14.8	113	2.7

5.8.1 Drastic Case Results

The results of the single block and cooperative control response to drastic load removal are plotted in Figure 5.18 and Figure 5.19. Before A, blocks output I_{max} . At A, the load is disconnected. From A to B, V_g increases. At B, $V_g = V_{peak}$ and is above the stable region. The MCU senses $V_g \geq V_{max}$ and the state machine transitions from the REGULATE state into the SLEEP state and sets $D_{PWM} = 0$. From C-E, I_L decreases from I_{max} to I_{NL} .

From B-F, V_g oscillates within the stable region. The measured results of V_g , the settling time of the system from A to F, t_{settle} and the time duration that V_g was sustained above the stable region, t_{over} are presented in Table 5.5.

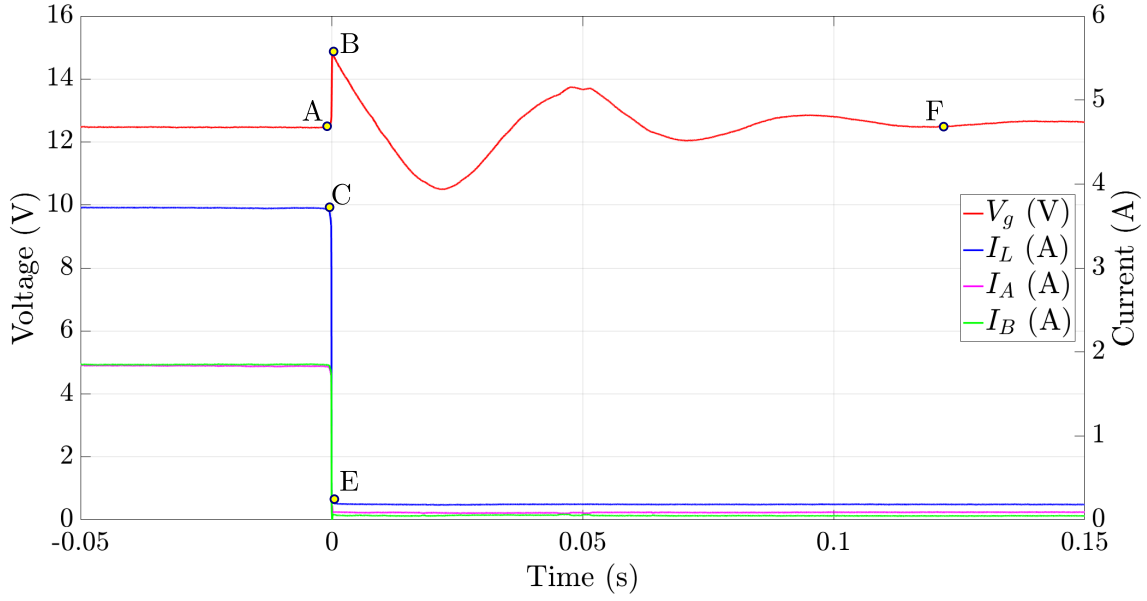


Fig. 5.19 Cooperative response to I_{max} to I_{NL} step.

5.8.2 General Case Results

When testing the general cases of load removal, two different control responses were observed. The results presented depict each response observed for a $2.5 \rightarrow 1.5$ A, $\Delta I_L = 1$ A load removal event. The results plot for each, of all the general load removal cases tested, are presented in Appendix D.

First Response

The results of the first response are plotted in Figure 5.20. At A the load was disconnected. From A-B, V_g increases. At B, $V_g = V_{peak}$ which is above the stable region. The MCU of both blocks senses $V_g \geq V_{max}$ and the state machine transitions from the REGULATE state into the SLEEP state. The control action within the SLEEP state sets $D_{PWM} = 0$. The effect of this is observed from C-E as all measured currents decrease. I_L decreases from $I_{initial}$ and undershoots I_{end} by I_{under} at E.

From B-x, V_g decreases. At x, V_g is in the stable region. The MCU senses $V_g \leq V_{max}$ and the state machine transitions from the SLEEP state into the REGULATE state. From x-z, V_g continues to decrease. At z, the MCU should sense $V_g \leq V_{nom}$ and increase D_{PWM} to prevent V_g decreasing out of the stable region. However, from z-F,

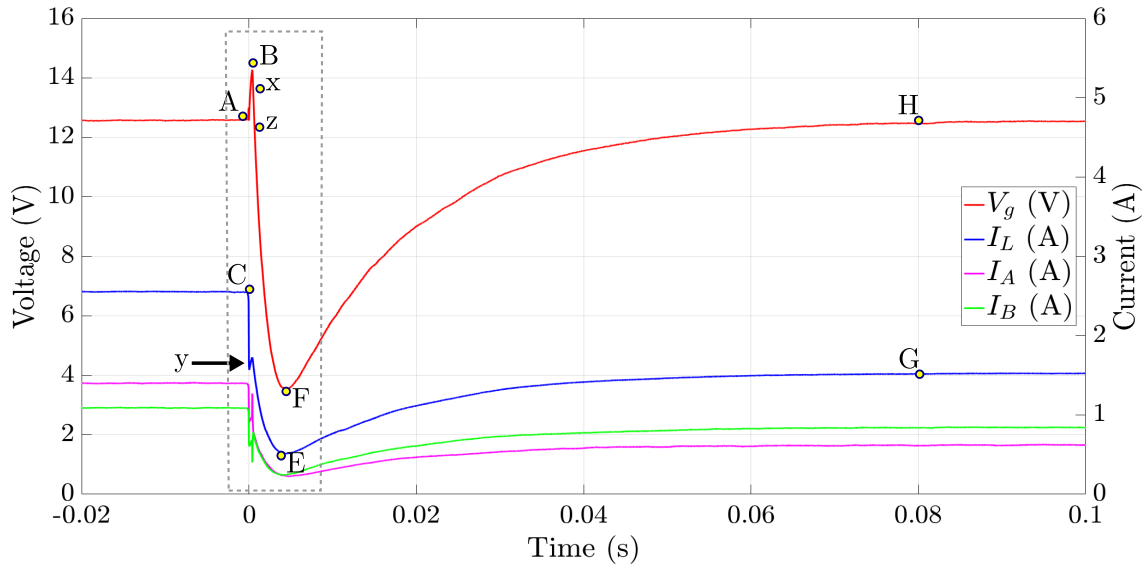


Fig. 5.20 First response to a general load removal event.

the control fails to keep V_g within the stable region. V_g undershoots V_{nom} by V_{under} at F. To understand why the control failed from z-F, the boxed area on Figure 5.20 is depicted by Figure 5.21.

First Response Discussion

Points annotated on Figure 5.20 are annotated at their same positions on Figure 5.21. The transient of concern is depicted on Figure 5.21, bounded by y_1 - y_2 and lasted for 0.5 ms. The increase in V_g from A-B occurs because there is an oversupply to the grid. When the MCU senses $V_g \geq V_{nom}$, the control responds by decreasing D_{PWM} and a decrease in the measured current is expected. Initially, from C- y_1 , the current decreases as expected. However, from y_1 - y_2 , the current unexpectedly increases. This increase in current from y_1 - y_2 is the oversupply to the grid after the load was removed which increases V_g .

The oversupply is caused by a discharge of power from the Flyback converters output capacitor after the load was removed. At B, the state machine transitions into the SLEEP state and D_{PWM} is set to 0. From B-x, $D_{PWM} = 0$ and the output capacitors remain discharged. At x, the state machine transitions into the REGULATE state. From x-z, the MCU senses $V_g \leq V_{nom}$. The state machine does not increase D_{PWM} and the output capacitors remain discharged. At z, the MCU senses $V_g \leq V_{nom}$. The state

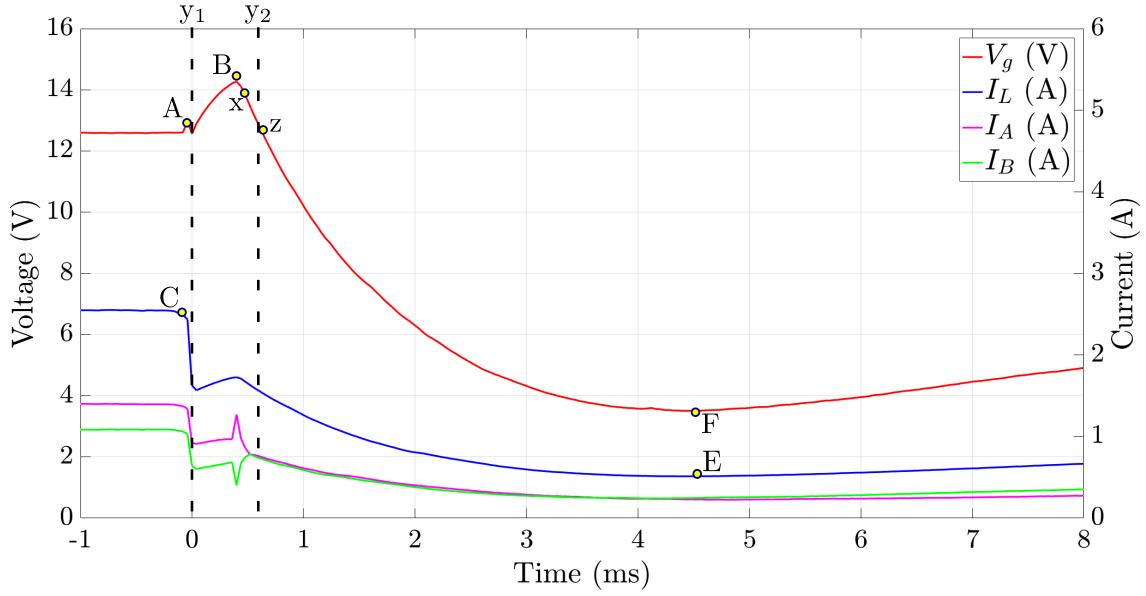


Fig. 5.21 First response transients observed during a general load removal event.

machine increases D_{PWM} and the output current is drawn by the capacitors charging. This explains why an increase in V_g from z-F is not observed despite the increase in D_{PWM} . At F, the output capacitors are charged and V_g begins to increase.

From F-H and E-G depicted on Figure 5.20, V_g and I_L increase until $V_g = V_{nom}$ and $I_L = I_e$ indicating the end of the load removal event. In the region bounded by y_1 - y_2 , a spike in I_A and a complimentary dip in I_A was observed. The peak of this spike in I_A occurs at the same moment in time that $V_g = V_{peak}$ at B. The time duration of the transient spike and dip was 0.08 ms. The cause of the transient spike and dip is unknown.

Second response

The results of the second response are plotted in Figure 5.22. At A the load was disconnected. From A-B, V_g increases and overshoots V_{nom} . At B, $V_g = V_{peak}$ which is above the stable region. The MCU controlling block B senses that $V_g \geq V_{max}$. The state machine transitions from the REGULATE state into the SLEEP state. The control action in the SLEEP state sets $D_{PWM} = 0$ and I_B decreases from C-E.

The MCU controlling block A does not sense that $V_g \geq V_{max}$. However, the MCU controlling block A does sense that $V_g \geq V_{nom}$. The state machine remains in the

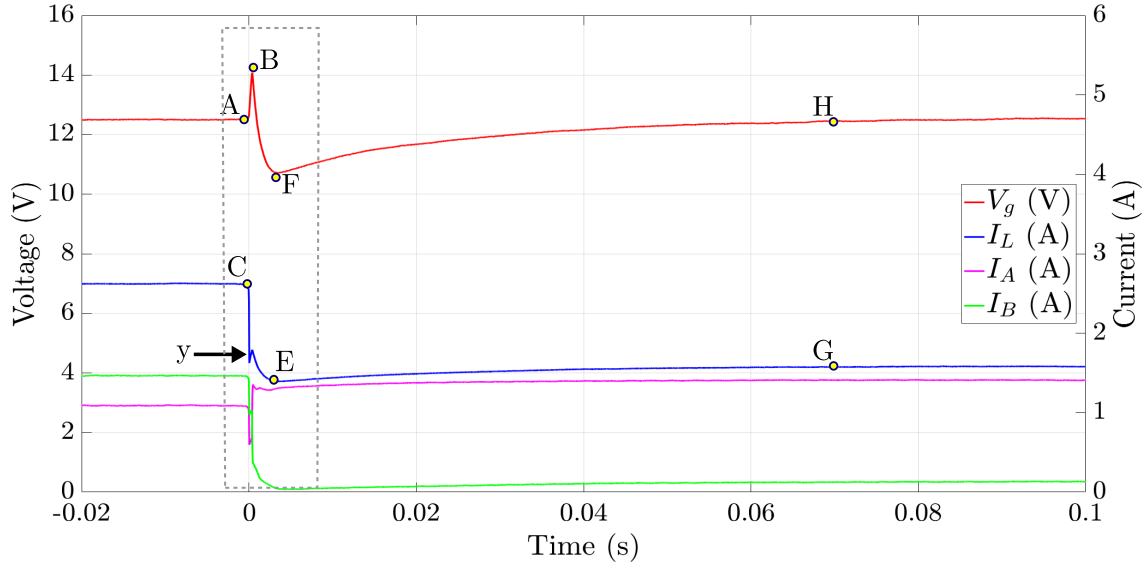


Fig. 5.22 Second response to a general load removal event.

REGULATE state and the control action decreases D_{PWM} and I_A decreases. From B-F, V_g decreases. V_g undershoots V_{nom} by V_{under} at F, but the control was able to keep V_g within the stable region. To understand why the control was successful, the boxed area on Figure 5.22 is depicted by Figure 5.23.

Second Response Discussion

Points annotated on Figure 5.22 are annotated at their same positions on Figure 5.23. The transient of concern is depicted on Figure 5.21, bounded by y_1 - y_2 and lasted for 0.5 ms. The increase in V_g from A-B occurs because there is an oversupply to the grid. When either blocks MCU senses $V_g \geq V_{nom}$, the control responds by decreasing D_{PWM} and a decrease in the measured current is expected. Initially, from C- y_1 , the current output from both blocks decreases as expected. However, from y_1 - y_2 , the current increases due to the capacitor discharge as discussed for the first response.

At x, I_A increases and I_B decreases. The decrease in I_B is explained by the MCU sensing $V_g \geq V_{max}$ and the state machine transitioning into the SLEEP state, setting D_{PWM} to 0. The increase in I_A is unexpected. An explanation for this unexpected result is that block A's MCU does not sense $V_g \geq V_{max}$ and the state machine does not transition into the SLEEP state. At x, block A's MCU senses $V_g \leq V_{nom}$ and

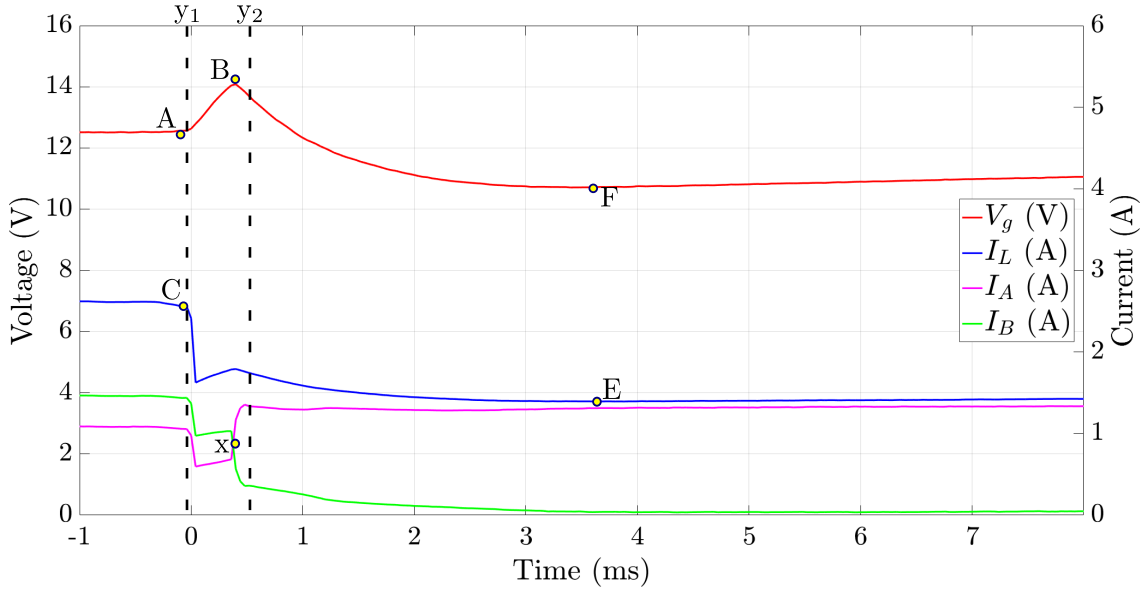


Fig. 5.23 Second response transients observed during a general load removal event.

increases D_{PWM} . However, at x, the results show that V_g is above the stable region and $V_g \geq V_{max}$. Block A's MCU does not sense this.

For the tests conducted, V_g was measured across the DC bus. A possible explanation as to why block A's MCU does not sense the same V_g as measured across the DC bus may be: Transmission losses between the DC bus and three port connection of block A cause V_g measured at the DC bus to not equal V_g sensed by the MCU at the three port connection. However, this was not the case for block B. Blocks connected to the grid will sense different grid voltages and will respond according to what is sensed. To validate this explanation, the test must be conducted with V_g measured at the three port connection of each block as well as across the DC bus.

Results for all Cases

Test results of all the tested load removal cases and the settling time of the system, t_{settle} are presented in Table 5.6. The dual response to load removal was not unique for the results presented in Figure 5.20 and Figure 5.22. A dual response was observed under several test conditions and results marked with an * in Table 5.6 indicate a second response. A plot of results for each, of all the general load removal cases tested, are presented in Appendix D.

Table 5.6 Response to general load removal events.

$I_i \rightarrow I_e$ (A)	ΔI_L (A)	V_{peak} (V)	V_{under} (V)	I_{under} (A)	t_{settle} (ms)	t_{over} (ms)
1 $\rightarrow$ 0.5	0.5	14.4	5.9	0.2	30	0.3
1.5 $\rightarrow$ 1	0.5	14.2	8.1	0.5	62	0.2
1.5 $\rightarrow$ 1 *	0.5	14.1	-	-	52	-
2 $\rightarrow$ 1.5	0.5	14.1	0.9	-	50	-
2.5 $\rightarrow$ 2 *	0.5	13.8	-	-	47	-
2 $\rightarrow$ 1	1	14.2	8.1	0.5	60	0.1
2.5 $\rightarrow$ 1.5	1	14.3	9	1	69	0.1
2.5 $\rightarrow$ 1.5 *	1	14	1.8	0.1	63	-
3 $\rightarrow$ 2	1	14.2	9.8	1.5	86	0.1
3 $\rightarrow$ 2 *	1	14.1	1.3	0.1	62	0.1
2 $\rightarrow$ 0.5	1.5	14.5	5.9	0.2	32	0.1
3 $\rightarrow$ 1.5	1.5	14.4	9.1	1	74	0.1
3 $\rightarrow$ 1.5 *	1.5	14.2	-	-	9	0.1
3 $\rightarrow$ 1.5 *	1.5	14.2	-	-	9	0.1
3 $\rightarrow$ 1	2	14.4	8.2	0.5	64	0.1
3 $\rightarrow$ 0.5	2.5	14.8	5.8	0.2	30	0.4

The results highlighted in green are for the responses depicted by Figure 5.20 and Figure 5.22.

The result highlighted in blue indicates the best case result to a load removal event that was observed. For this case, no voltage or current undershoot was observed and the shortest t_{settle} was measured.

The result highlighted in red indicates the worst case result to a load removal event that was observed. The results for this case have the largest grid voltage overshoot and time duration spent above the stable region.

Considering all of the load removal cases tested. V_g increased to an average of $V_{peak_{ave}} = 14.2$ V and the average time duration that V_g spent above the stable region was $t_{over_{ave}} = 0.2$ ms. The average settling time was $t_{settle_{ave}} = 52$ ms. From the 11 general cases tested, 5 exhibited a dual response. The results plot of the control response for the worst and best case load removal events are presented in Section 5.9.

5.8.3 Discussion

The control response to a load removal event was established. An increase in V_g was observed when a load was disconnected from the grid due to a transient oversupply on the grid. The oversupply was caused by the discharge of the Flyback converters output capacitors after the load was disconnected. The addition of battery storage on the grid will stabilise V_g during load removal. In the event of an oversupply, the ES block will absorb the excess power to charge the battery element. This should eliminate or reduce the magnitude of the increase in V_g when a load is disconnected. Results show that $\Delta I_L \propto V_{peak}$. This means that the larger the load removed from the grid, the greater the oversupply and thus the greater the magnitude of increase in V_g .

An investigation into predicting and controlling the MCU response to a load removal event was beyond the scope of this research. This topic is related to the autonomous nature of the PeCo grid and how blocks coordinate power flow and perform load sharing to ensure V_g is kept within the stable region. A recommendation for future research is to further investigate the explanation given regarding the discrepancy in V_g measured across the DC bus to the V_g sensed at the three port connection of a block.

5.9 Comparison Between Control Platforms

The response of the Legacy Grid's control platform to a load removal event was presented in Chapter 1. A shortcoming of the Legacy Grid was that the response was not fast enough and caused an excessive oversupply to the grid after the load was removed. This resulted in a drastic and sustained increase of V_g above the stable region.

The second research sub-question asked was:

"How will a control platform that responds faster than the Legacy Grid control platform respond to a load removal event and will the response be improved?"

Now that the MCU response to a load removal event has been established, it can be compared to the response of the Legacy Grid's control platform to answer the second research sub-question. As discussed in Chapter 1, the response will be considered

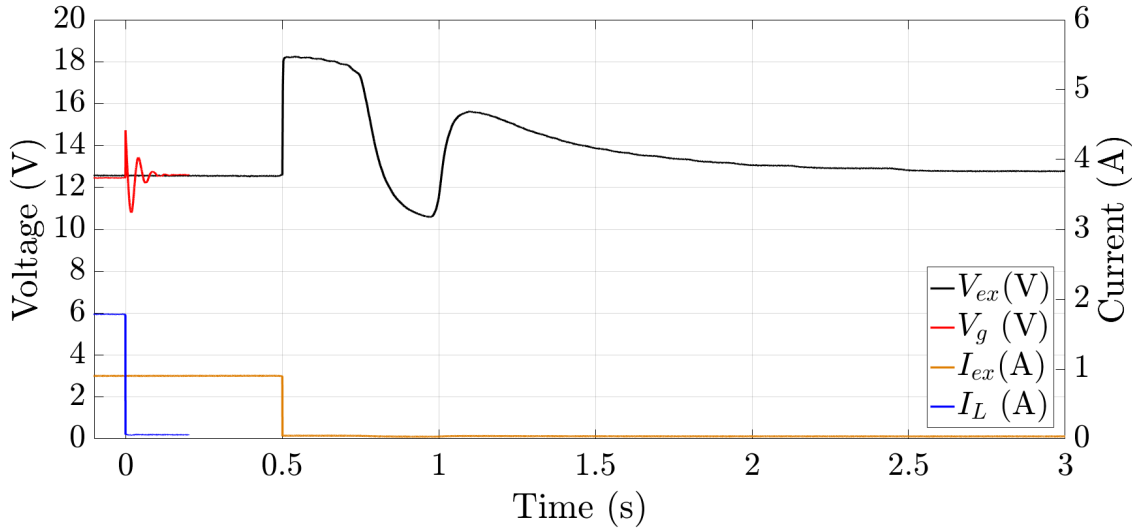


Fig. 5.24 Single block MCU drastic response compared to Legacy Grid response.

Table 5.7 Comparison of the control platform responses to a load removal.

Response	V_{peak} (V)	t_{over} (ms)	t_{settle} (ms)
Legacy Grid	18	300	2040
MCU _{single}	14.8	2.4	102
MCU _{cooperative}	14.8	2.7	113
MCU _{best}	14.2	0.1	9
MCU _{worst}	14.8	0.4	30

improved if the settling time of V_g , t_{settle} is faster and if the increase in V_g above the stable region, is reduced in both magnitude V_{peak} and duration t_{over} .

The MCU single block and cooperative response to a drastic load removal and the worst and best case response to a general load removal were selected to be compared to the Legacy Grid's response. Figures 5.24 to 5.27 depicts the comparison of each of the MCU transient responses plotted on the same time scale as the Legacy Grid response. The grid voltage and load current controlled by the Legacy Grid are represented by V_{ex} and I_{ex} . The grid voltage and load current controlled by the MCU are represented by V_g and I_L . The load is removed at $t = 0$ s and at $t = 0.5$ s for the MCU and Legacy Grid respectively. Table 5.7 compares the settling time, the magnitude of the peak increase in V_g and the time duration for which V_g was above the stable region for each response.

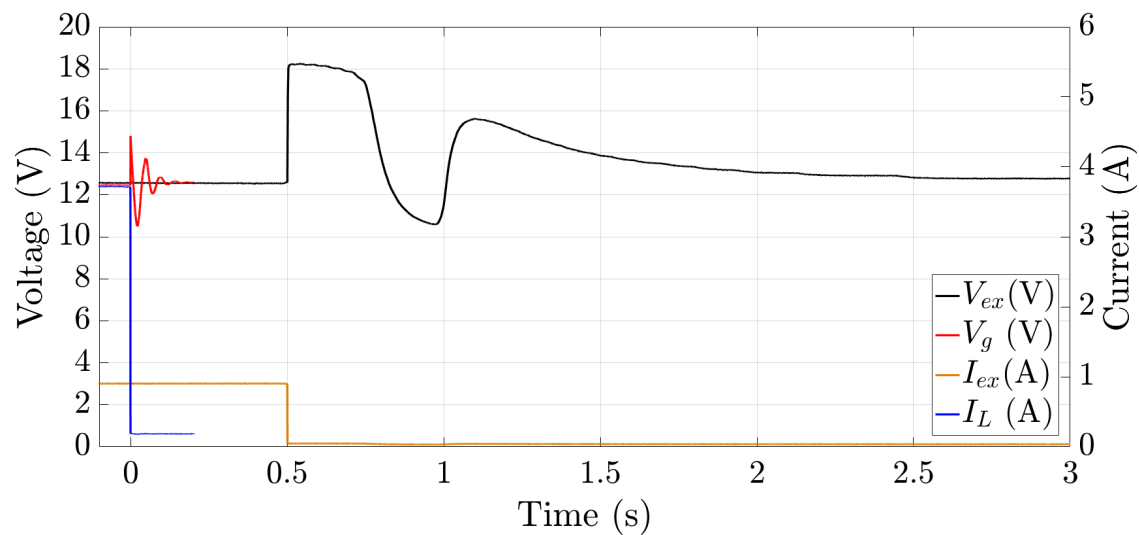


Fig. 5.25 Cooperative MCU drastic response compared to Legacy Grid response.

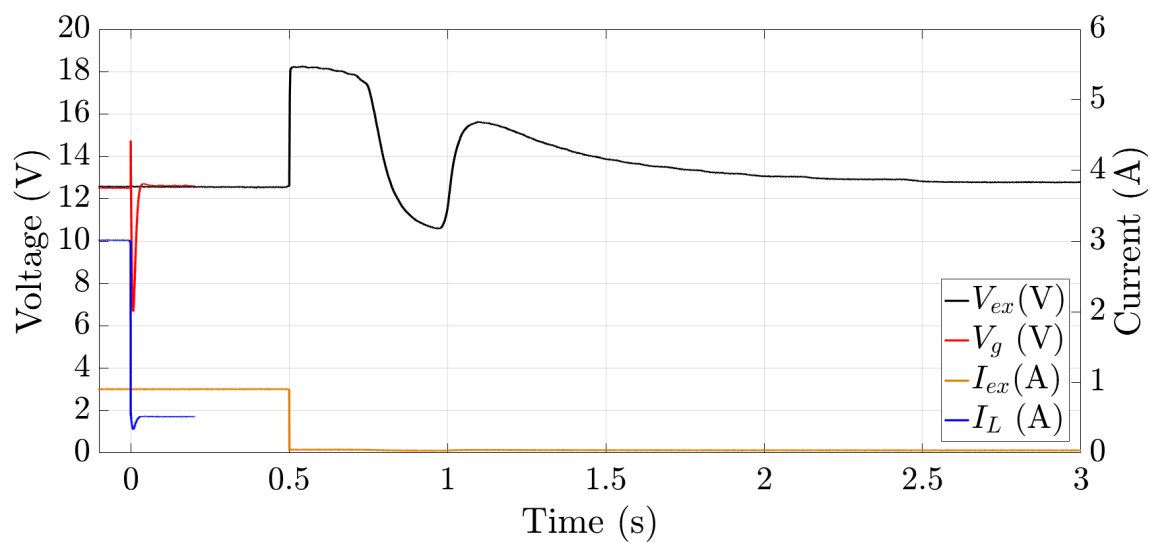


Fig. 5.26 Worst case MCU response compared to Legacy Grid response.

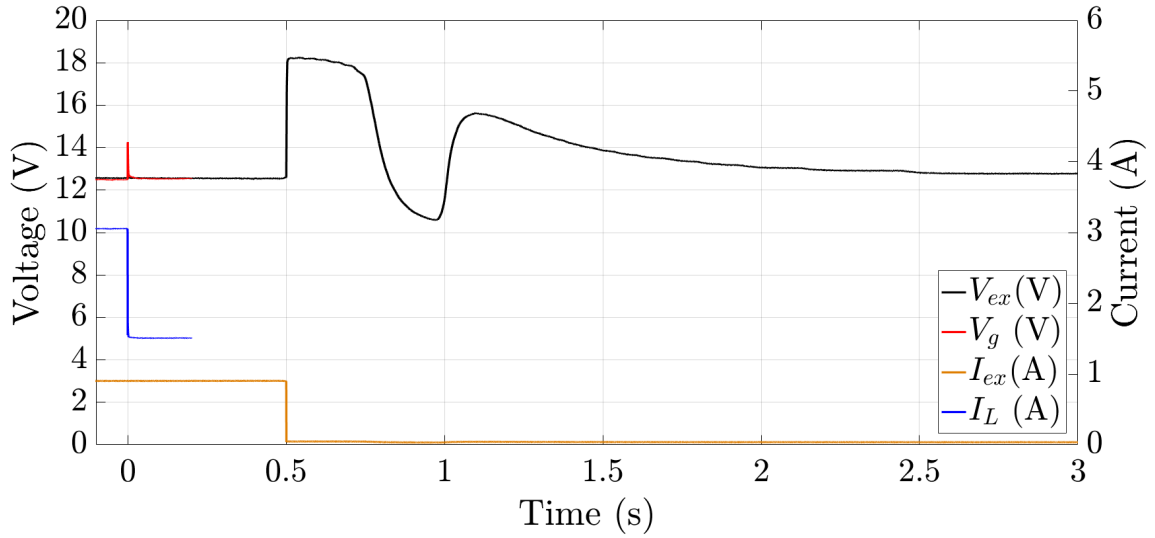


Fig. 5.27 Best case MCU response compared to Legacy Grid response.

Figures 5.24 to 5.27 depict a clear improvement in response to a load removal event by using the MCU control platform solution. The results compared in Table 5.7 show that the settling time of the MCU is faster, the magnitude of V_{peak} is reduced and the time duration that V_g remains above the stable region is shortened.

5.10 Concluding Remarks

The accomplishment of the fifth research objective was communicated in this chapter. The control strategy was revised and adapted to be deployed on the MCU. Adaptation entailed modelling the control strategy as a state diagram in software and deploying it on the MCU. Tests were conducted to evaluate the control strategy. Results validated the autonomous operation, fault tolerance and coordinated control of power flow between blocks connected to the grid.

The MCU control response to loading and load removal events on the grid was tested. Results showed that during loading a transient undersupply will occur and that during load removal a transient oversupply will occur. The MCU response to these transients was fast enough to prevent a catastrophe on the grid. This answered the second research sub-question and validates that the shortcoming of the Legacy Grid has been overcome.

Chapter 6

Model-based MPPT

A model-based MPPT solution that estimates the PV module current obviates the need for a current sensor in a PV system. The mathematical model derived for the primary-side inductor current of a DCM Flyback converter in Chapter 4, was deemed suitable to be applied for model-based MPPT.

In this Chapter, a model-based MPPT solution is formulated. The real world application of the interface developed throughout this research is tested using the PeCo grid as a test platform. The accomplishment of the sixth and seventh research objectives and answer to the third research sub-question are communicated.

6.1 Maximum Power Point Tracking

The characteristic voltage-current (V-I) and power curve of a PV module are depicted in Figure 6.1. These curves are non-linear and vary with solar irradiation availability and temperature. The premise for MPPT is to shift the operating point (OP) on the V-I curve to track the MPP on the power curve.

Maximum power can only be delivered from a PV module if there is sufficient load demand to accept it. The solar GEN block depicted by Figure 6.2 is a PV system. Under the context of the PeCo grid, it is primarily tasked with charging the battery elements of the ES blocks during the day so that it can be used for power generation at night. A depleted battery element interfaced to the PeCo grid serves as a sink for

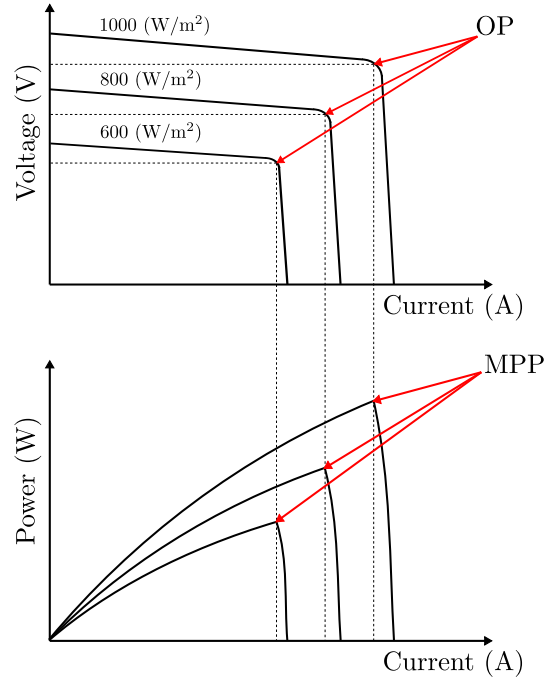


Fig. 6.1 V-I relationship at varying solar irradiation levels and the characteristic power curve of a PV module.

any excess power on the grid not delivered to the loads. If $P_{mpp} > P_{load}$, the excess power delivered to the battery is $P_{bat} = P_{mpp} - P_{load}$.

6.1.1 MPPT Algorithms

The model derived in Chapter 4 is only applicable to MPPT algorithms where I_{pv} is a required sensed parameter. Work done by [54] reviews and compares 19 different

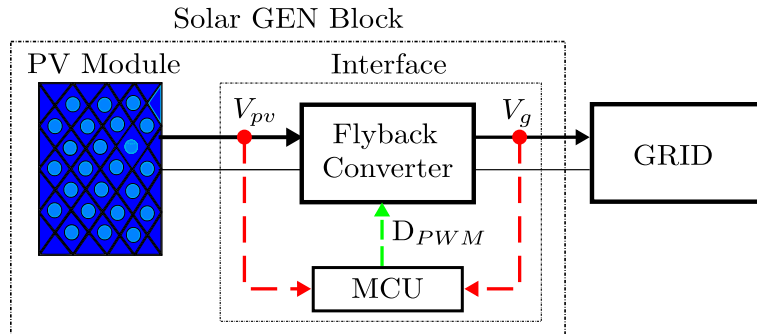


Fig. 6.2 Solar GEN block.

MPPT algorithms. I_{pv} is a required sensed parameter for 12 of these algorithms. The perturb and observe (P&O) algorithm preferred over other MPPT algorithms for its simplicity and ease of use [55, 56, 54, 57]. It is one of the most common and widely used MPPT algorithms [55, 56, 54, 57].

6.1.2 Perturb and Observe Algorithm

The P&O algorithm is an iterative approach to finding the MPP by perturbing the operating point of the PV module towards the MPP by increasing or decreasing D_{PWM} . Figure 6.3 depicts the methodology of the P&O algorithm on the characteristic power curve of a PV module. The algorithm requires the change in power ΔP_{pv} and change in operating voltage ΔV_{pv} between iterations to determine if the operating point is before or after the MPP. If $\Delta P_{pv}/\Delta V_{pv} > 0$, the operating point is approaching the MPP and the control action decreases D_{PWM} to perturb positively. If $\Delta P_{pv}/\Delta V_{pv} < 0$, the operating point is past the MPP and the control action increases D_{PWM} to perturb negatively. The P&O algorithm does not settle the operating point at the MPP and instead oscillates about it. There is thus always an expected error between the actual MPP and the output power.

Figure 6.4 depicts the block diagram of the P&O MPPT algorithm. Each iteration begins by sensing $V_{pv(n)}$ and $I_{pv(n)}$. $P_{pv(n)}$ is calculated from $V_{pv(n)}$ and $I_{pv(n)}$ and the change in power ΔP_{pv} is calculated from the difference between $P_{pv(n)}$ and the power calculated from the previous iteration $P_{pv(n-1)}$. Following this, ΔV_{pv} is calculated in a similar manner and the algorithm transitions performs the required control action.

6.1.3 Model-based Current

Conventionally I_{pv} is sensed using a current sensor such as a sense resistor. The model derived in Chapter 4 estimates the primary side inductor current of a DCM Flyback converter. Applying this model to estimate I_{pv} obviates the need for a current sensor. The premise for taking a model-based approach is to reduce cost. Figure 6.5 depicts the current flow between the PV module and the primary side of the Flyback converter. The control platform current, I_{cp} must be added to the estimated inductor current I_p to calculate I_{pv} which is expressed by:

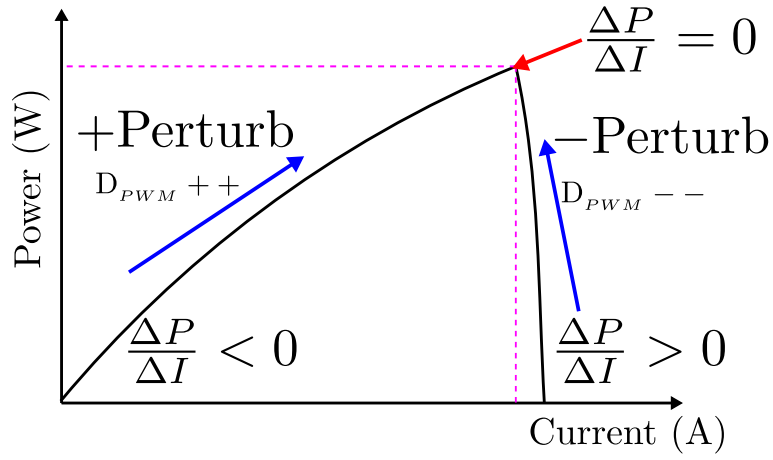


Fig. 6.3 Methodology of the P&O MPPT algorithm.

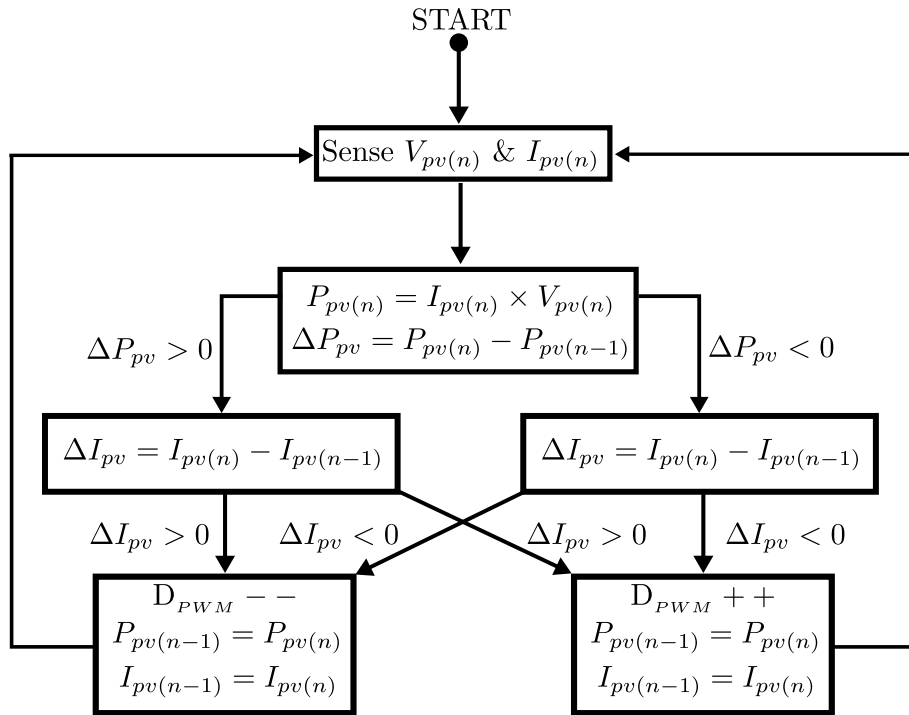


Fig. 6.4 Block diagram of the P&O MPPT algorithm.

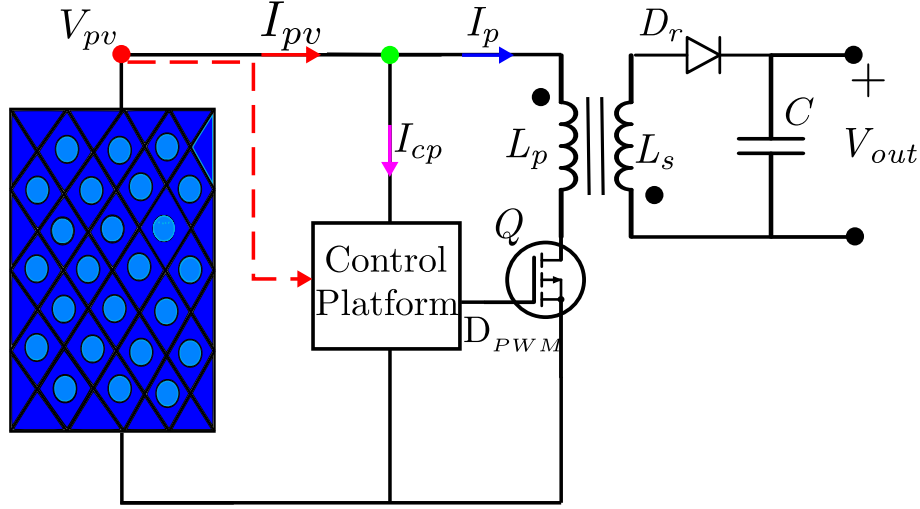


Fig. 6.5 Schematic depicting current flow from the PV module.

$$I_{pv} = \frac{V_{pv} \times D_{PWM}^2 \times T}{2 \times L_p} + I_{cp} \quad (6.1)$$

The P&O algorithm was adapted to include equation 6.1, see Figure 6.6. The algorithm no longer requires $I_{pv(n)}$ to be sensed and can estimate $I_{pv(n)}$ and $P_{pv(n)}$ from $V_{pv(n)}$.

6.2 MPPT State

The MPPT state was introduced in Chapter 5. The model-based P&O MPPT algorithm was modelled in software as a state diagram and embedded into the MPPT state, see Figure 6.7. When $V_{MPPT_L} \leq V_g \leq V_{MPPT_H}$ evaluates to true, the state machine transitions from the REGULATE state into the MPPT state and the model-based P&O MPPT algorithm is executed.

The change in D_{PWM} , ΔD_{PWM} , made after each iteration of the algorithm was kept constant at $\Delta D_{PWM} = 0.0025\%$. A time delay of $t_{mppt} = 1$ s was applied after each iteration to allow for the system to settle before performing the next iteration. D_{PWM} was adjusted at a rate of 1 %/s. $V_{MPPT_L} = 12.4$ V and $V_{MPPT_H} = 12.7$ V.

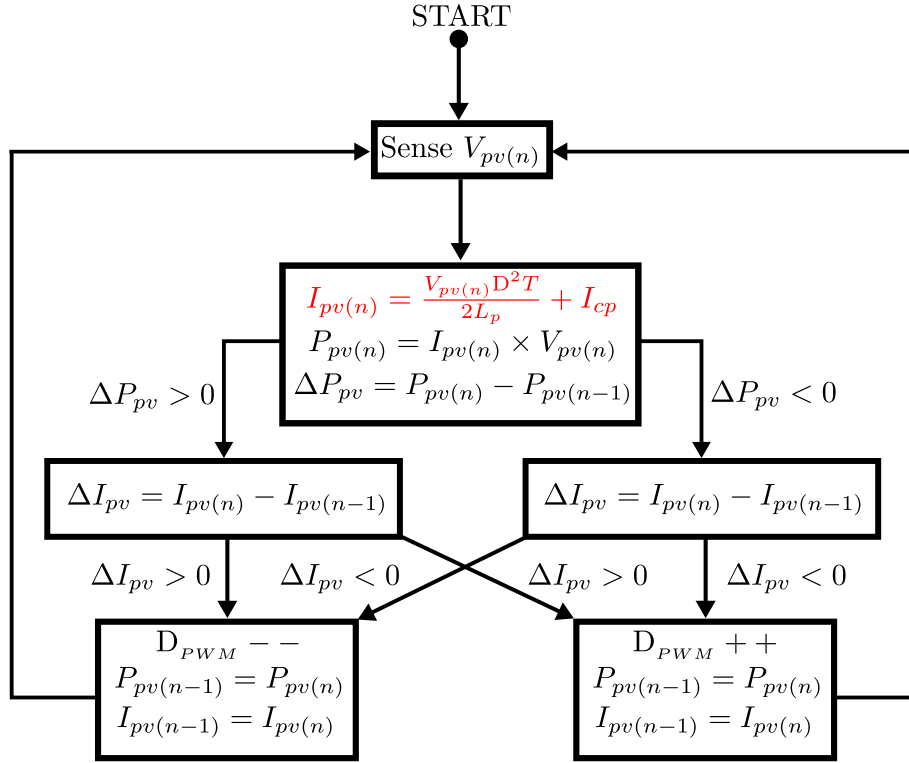


Fig. 6.6 Block diagram of the P&O MPPT algorithm with model-based current.

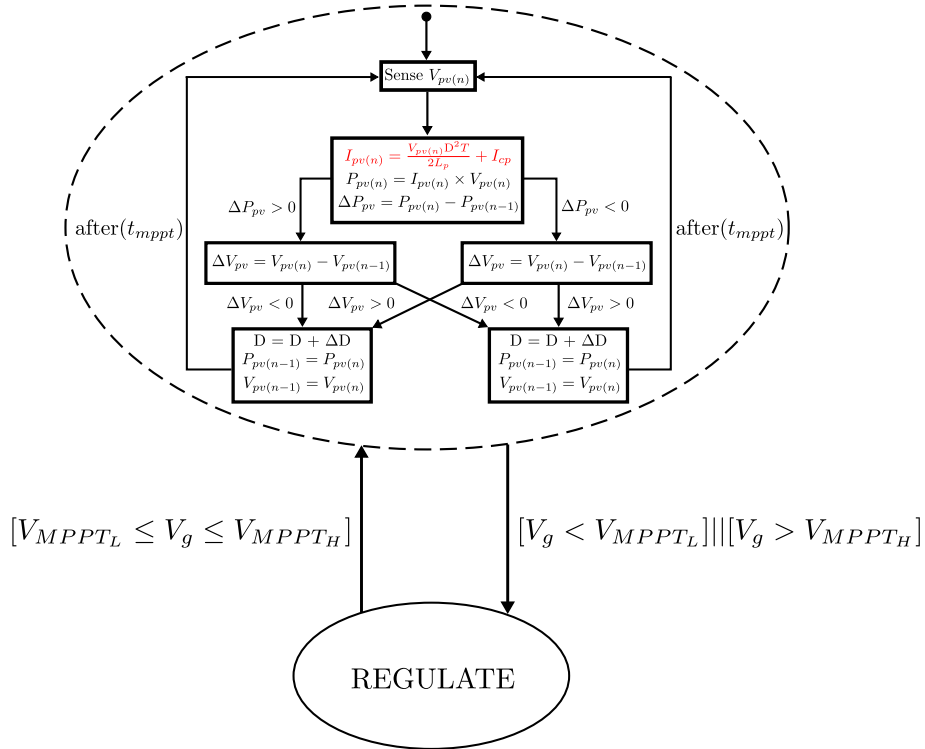


Fig. 6.7 Control action within and transitions to and from the MPPT state.

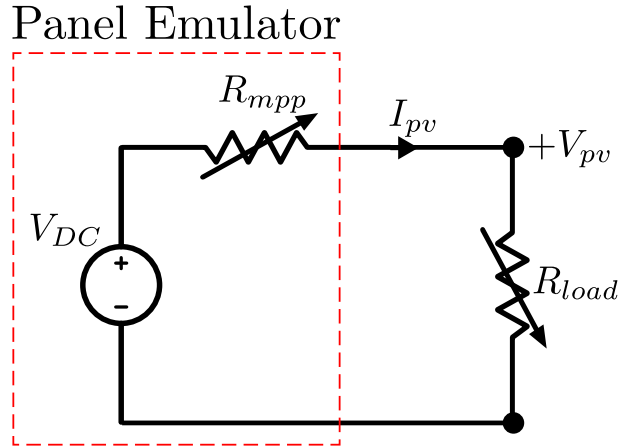


Fig. 6.8 Circuit to emulate a PV module using a DC power supply and a series resistor.

6.3 PV module Emulator

A DC power supply with an adjustable current limit and a resistor R_{mpp} were connected in series, see Figure 6.8. By setting the current limit of the DC power supply to I_{mpp} and the output voltage V_{DC} to the open circuit voltage of the PV module, R_{mpp} can be adjusted to set V_{mpp} according to the following equation:

$$R_{mpp} = \frac{V_{DC} - V_{mpp}}{I_{mpp}} \quad (6.2)$$

Using this PV emulator, PV module characteristic I-V and power curves with various MPP can be emulated as depicted by Figure 6.9. Emulated curves were acquired by connecting the load R_{load} at the output of the PV emulator and performing a sweep through R_{load} from an open-circuit to a short-circuit whilst measuring V_{pv} and I_{pv} . V_{pv} was plotted against I_{pv} , see Figure 6.9a. P_{pv} was calculated from V_{pv} and I_{pv} . P_{pv} was plotted against V_{pv} , see Figure 6.9b.

6.4 MPPT Validation Test

This test was conducted to validate if the model-based MPPT can track a MPP emulated by the PV emulator. A PeCo grid consisting of one ES block and one GEN block was built. The ES block interfaced a depleted 12 V lead acid battery element to

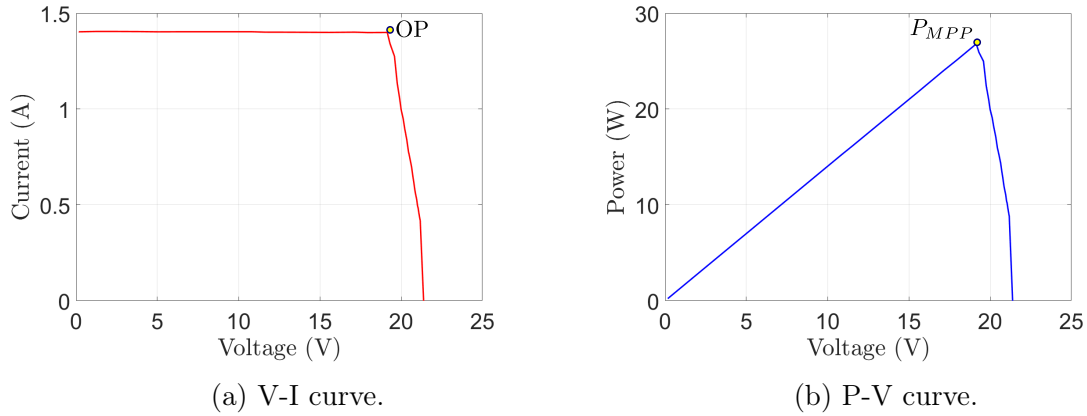


Fig. 6.9 Emulated characteristic V-I and power curve for a 27 W MPP.

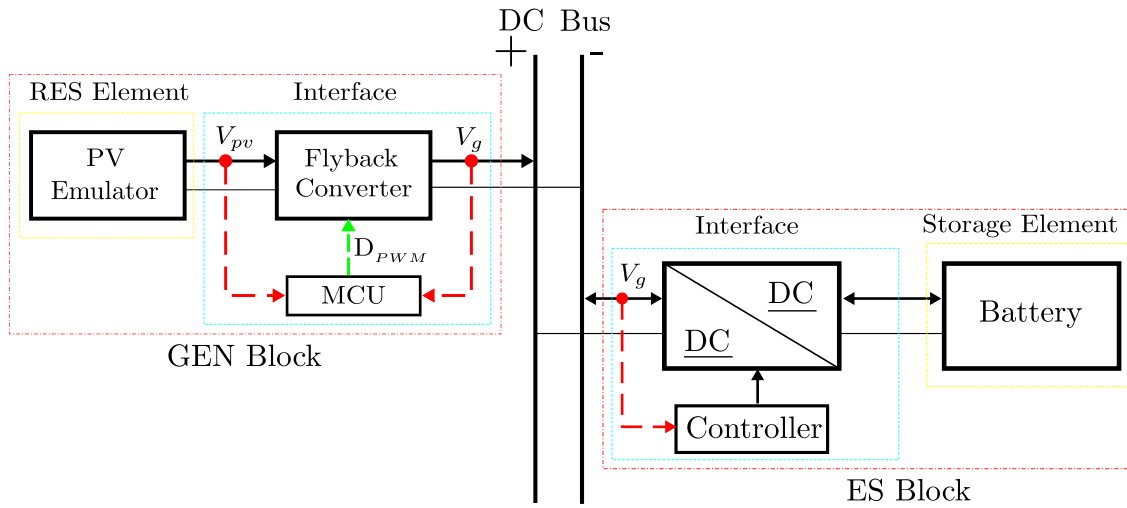


Fig. 6.10 PeCo grid built to validate the model-based MPPT.

the grid and the GEN block interfaced the PV emulator to the grid, see Figure 6.10. The premise for this test was to emulate the charging of a battery element by a PV module on the PeCo grid. Table 6.1 lists the parameters that were set to emulate three different MPP's. The PV emulator voltage and current, V_{pv} and I_{pv} , and the grid voltage and output current from the GEN block, V_g and I_g , were measured over a 10 minute period for each emulated MPP. The power from the PV emulator and power to the grid, P_{pv} and P_g , were calculated from the measured variables.

Table 6.1 Parameters set for PV module emulation.

P_{mpp} (W)	V_{DC} (V)	V_{mpp} (V)	I_{mpp} (A)	R_{mpp} (Ω)
10	22	17.7	0.6	7
20	22	17.7	1.1	4
30	22	17.7	1.7	2.5

Table 6.2 MPPT validation test results.

P_{mpp} (W)	$\overline{P}_{pv}$ (W)	Error	$\overline{P}_g$ (W)	$\overline{\eta}$	$\overline{V}_g$ (V)
10	9.6	4%	7.2	75%	12.6
20	19.1	4%	14.3	74.9%	12.6
30	29.1	3%	21.8	74.8%	12.6

6.4.1 Results

Figures 6.11 to 6.13 depicts the results of P_{pv} , P_g and V_g measured over the 10 minute period for each of the emulated P_{mpp} cases. Table 6.2 lists the results of the MPPT validation test. The average results are presented in Table 6.2.

6.4.2 Discussion

Figure 6.11 validates that the model-based MPPT solution can track a MPP. Figure 6.13 shows that V_g was kept within the stable region bounded by V_{MPPT_L} and V_{MPPT_H} whilst MPPT was being performed. MPPT was achieved without the need for any current sensors at the interface of the PV emulator to the PeCo grid. The test results validate the model-based MPPT solution. Test results communicate the accomplishment of the sixth objective of this research.

The efficiency of the Flyback converter whilst MPPT was being performed matched the efficiency of the Flyback converter determined during the power and efficiency test in Chapter 3, Section 3.5. The error in Table 6.2 was due to the power oscillation of P_{pv} about P_{mpp} . The error can be reduced by implementing a variable step MPPT as presented in the work done by [58] and [59]. By varying the step size of ΔD_{PWM} according to how near or far the operating point is from the MPP, the oscillations will be reduced. A recommendation for future research is to add the variable step MPPT concept to the model-based MPPT.

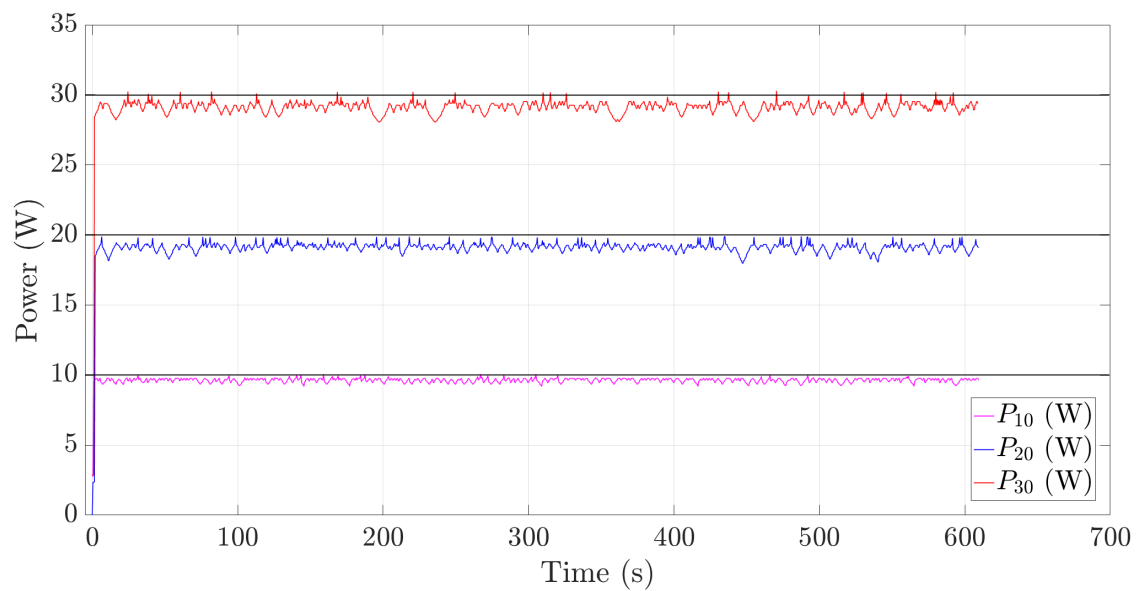


Fig. 6.11 Results of the MPPT for the emulated MPP's.

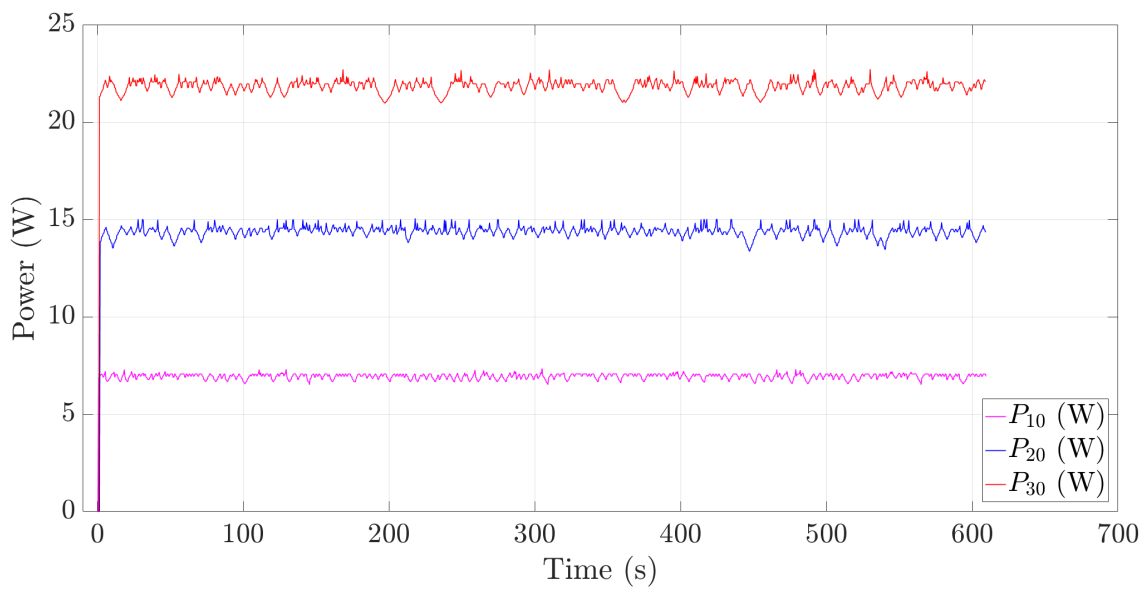


Fig. 6.12 Results of the output power for various input MPP's.

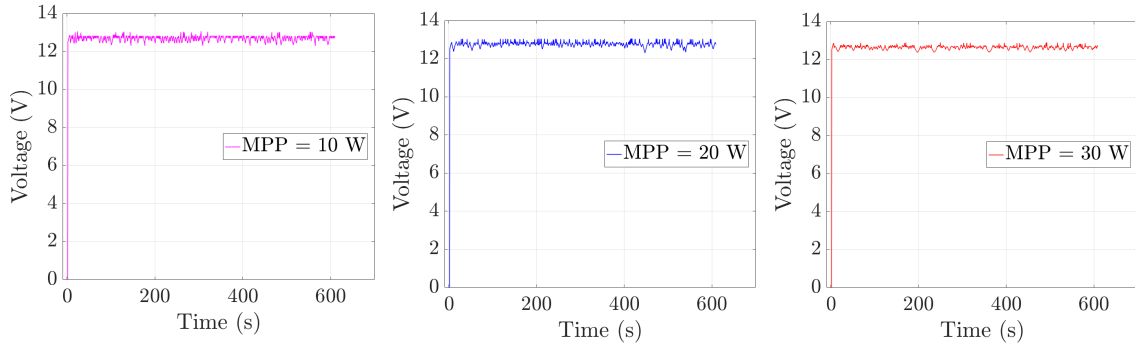


Fig. 6.13 Results showing the grid voltage fluctuation whilst MPPT is being performed.

6.5 Real World Application Test

This test was conducted to consolidate the entirety of this research and to validate that the interface developed is viable for rural electrification.

The hardware developed in Chapter 3 was used to connect the SLP030-12U PV module to a PeCo grid. The PV module combined with the interface forms a PV system. This PV system is controlled by the stigmergic based control strategy developed in Chapter 5. The PV system does not have any current sensors at the interface and implements a model-based MPPT solution developed in Chapters 4 and 6. Operating under the context of the PeCo grid, this PV system is a solar GEN block.

A depleted 12 V lead acid battery element was connected to the PeCo grid via an interface for a battery element. This created a PeCo grid composed of one solar GEN block and one ES block, see Figures 6.14 and 6.15. The PV module and the batteries were wired to their respective outputs on the test bed. The solar GEN block was tasked with delivering power to charge the ES block over an 18 hour period from sunrise to sunset. This is a real-world application for which the interface was developed. I_{pv} and V_{pv} were logged in 15 s intervals to calculate P_{pv} throughout the day. The available solar irradiation was measured using a pyranometer.

6.5.1 Results

Figure 6.16 compares the power output from the PV module to the changes in available solar irradiance and temperature throughout the day. The available solar irradiance peaked at 12:00 at $E_{s_{peak}} = 995 \text{ W/m}^2$. The output power from the PV module peaked

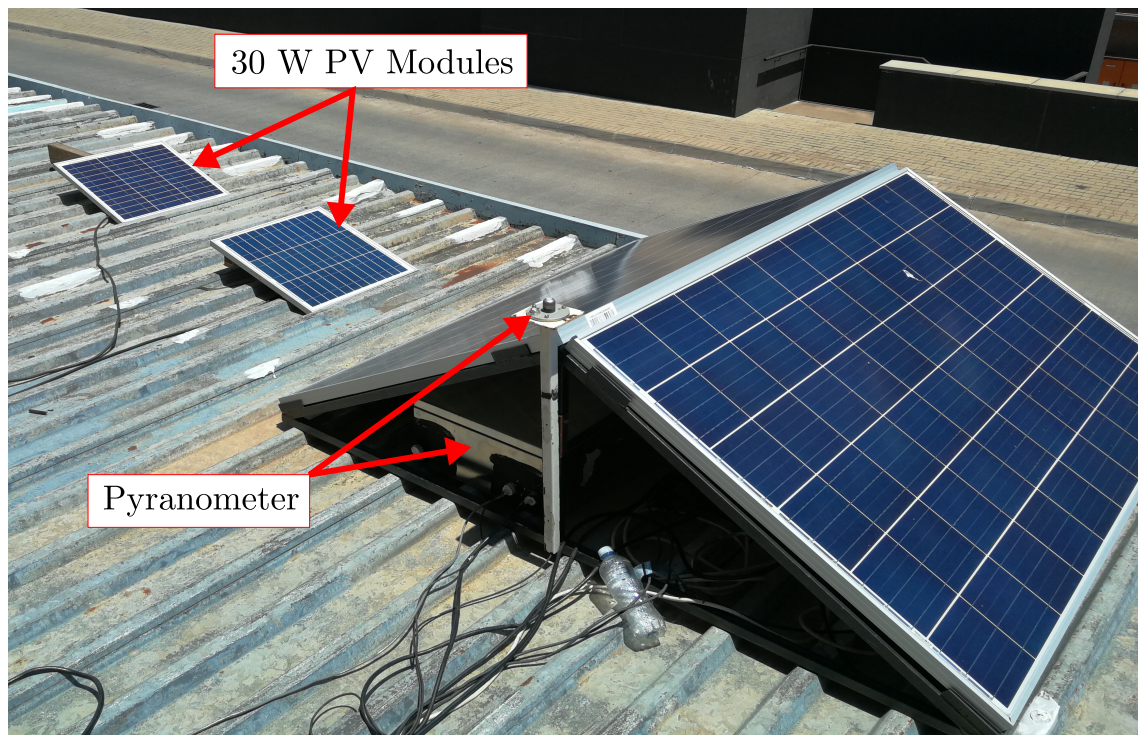


Fig. 6.14 Outdoor test set-up depicting the PV modules and pyranometer.

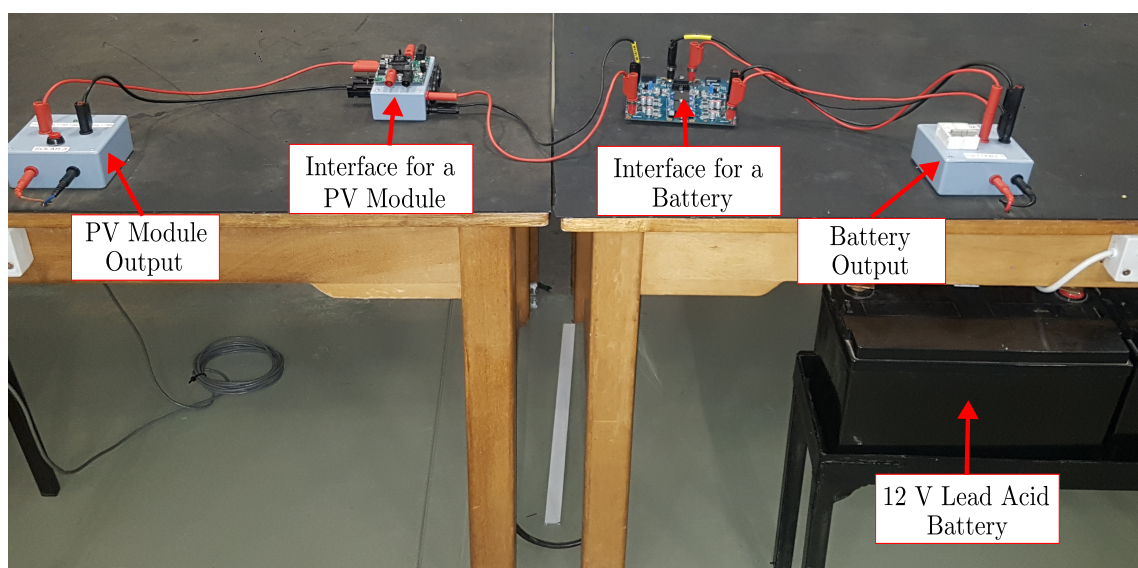


Fig. 6.15 Indoor test bed set-up depicting the interfaces for battery and PV module.

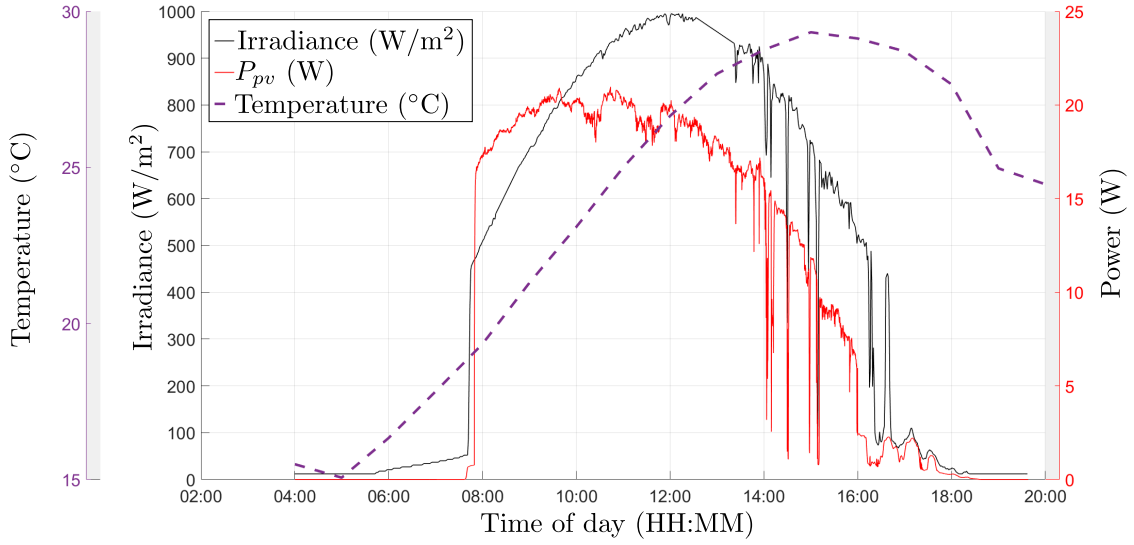


Fig. 6.16 Results comparing the power output from the PV module to the solar irradiance and ambient temperature throughout the day.

between 09:00 and 11:00. The peak output power measured was $P_{pv_{peak}} = 21$ W. Sharp dips in the power output and solar irradiance between 14:00 and 16:00 indicate cloud cover. The impact of the temperature on the power output from the PV module is most apparent between 12:00 and 16:00. The average temperature during this period was $T_{12:00-16:00} = 28^{\circ}\text{C}$, and the peak temperature measured for the day was $T_{peak} = 29^{\circ}\text{C}$. Figure 6.17 compares cumulative energy harvested throughout the day to P_{pv} . The total energy harvested was $E_{total} = 502083\text{J}$.

6.5.2 Discussion

P_{pv} followed the trend of the available solar irradiance and temperature. As the availability of solar irradiance increased, so did P_{pv} but as the temperature increased, P_{pv} decreased. This relationship is most apparent by comparing the results at 08:00 and 16:00. The available solar irradiance was $E_s = 508$ W/m^2 at 08:00 and 16:00, but P_{pv} was $P_{pv_{08:00}} = 17.5$ W and $P_{pv_{16:00}} = 6.3$ W. This difference in P_{pv} highlights the impact of temperature. The temperature at these times was $T_{08:00} = 19^{\circ}\text{C}$ and $T_{16:00} = 29^{\circ}\text{C}$. Even though there was equal solar irradiance available, the rise in temperature reduced P_{pv} by 36%.

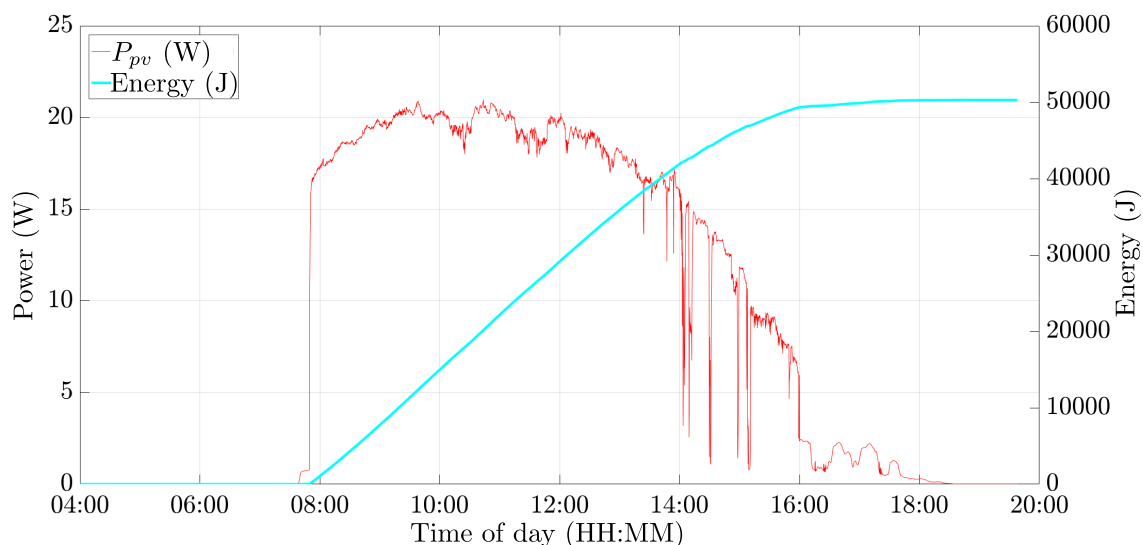


Fig. 6.17 Results of the power output from the PV module and the cumulative energy harvested over the day.

Ideally, the temperature on the PV module should be measured as opposed to the ambient temperature. The ambient temperature does not give a clear indication of the actual temperature of the PV module. To maximise P_{pv} , the temperature impact needs to be addressed. A recommendation for future research is to devise a solution for mounting the PV module to keep it cool. Installing the PV module on a rooftop is not recommended. Knowledge of the actual PV module temperature will aid in the design of the solution.

The test results validate that the PV module was successfully interfaced to the PeCo grid and operated under the PeCo grid context. The real world application test consolidates the entirety of the work done throughout this research and validates that the interface developed for a PV module to the PeCo grid is viable for rural electrification. Test results communicate the accomplishment of the seventh research objective.

6.6 Concluding Remarks

The third research sub-question asked was:

"How can the PeCo grid be used as a platform to formulate a model-based MPPT solution for a PV system?"

A model-based MPPT solution was formulated to be executed on the MCU at the interface for a PV module to the PeCo grid. The Flyback converter at the interface, operated in DCM, was used to derive an initial mathematical model to estimate the primary-side inductor current. This model was then combined with the P&O MPPT algorithm and modelled within the MPPT state of the control strategy. The model-based MPPT solution was validated on the PeCo grid. The model-based MPPT solution is not unique to the PeCo grid and may be applied to any PV system with the following constraints:

- The PV system must use a Flyback converter operated in DCM to transfer power between the PV module and load/ grid.
- The MPPT algorithm used by the PV system must require the PV module current as a sensed parameter.

Chapter 7

Conclusion

7.1 Document Summary

The PeCo grid was conceptualised as an ad-hoc, low voltage, DC distributed grid which uses solar and wind sources for energy generation and battery elements for energy storage. The purpose of the PeCo grid is to provide an autonomous, robust, resilient, low-cost, scalable, plug-and-play, rural household electrification solution. The features of the PeCo grid were validated on an experimental prototype grid, the Legacy Grid. However, the Legacy Grid did not interface actual solar or wind sources or battery elements to the grid. Instead, DC power supplies were interfaced to the Legacy Grid to emulate sources. To further the PeCo grid from a conceptual prototype to becoming a viable rural electrification solution, the Legacy Grid technology was advanced.

Advancement of the Legacy Grid technology entailed developing an interface for a PV module to the PeCo grid. The main components at the interface are a DC-DC power converter and control platform. The DC-DC converter matches the voltage levels of the PV module and the grid and the control platform regulates power flow from the PV module to the grid. The PV module, control platform and DC-DC converter are collectively termed a solar GEN block. The DC-DC converter was adopted from the Legacy Grid and is a Flyback converter operated in DCM. The Legacy Grid's control platform was not adopted. The response of the Legacy Grid's control platform to a load removal event on the grid was delayed and caused an oversupply to the grid after the load was removed. To overcome this, the control platform selected for the

interface of the PV module was a MCU that processes faster than the Legacy Grid's control platform. The adopted Flyback converter design was adapted to cater for an onboard MCU. The Flyback converter's transformer design was adapted to cater for a PV module.

PV systems perform MPPT to track the MPP of a PV module under varying availability of solar irradiance and temperature. The premise for the majority of MPPT algorithms is to sense the PV module voltage and current to calculate the power. Once the PV module power is known, control adjusts the operating point of the PV module until the MPP is reached. The conventional technique to sense current is to use a sense resistor. A drawback to this technique is the power loss and invasive nature. To overcome the drawbacks of the sense resistor technique, a mathematical model was derived to estimate the primary side-inductor current of a DCM Flyback converter. This model was validated to accurately estimate current and deemed suitable for a model-based MPPT solution. A model-based MPPT solution would obviate the need for any current sensors in a PV system and reduce the cost of the system.

Before formulating the model-based MPPT solution, the control strategy which regulates power flow from the PV module to the grid was developed. Finite state machine concepts were applied to model the control strategy as a state diagram. The inputs to the state diagram were the PV module voltage and grid voltage and the single output from the state diagram was the duty-cycle of the PWM signal switching the Flyback converter. The primary control objective was to ensure the grid voltage remains within a stable operating region and the secondary control objective was to perform MPPT. The following six states were created: SLEEP, PING, SOFT START, REGULATE, SATURATE and MPPT. The PING state protects the block from short-circuit and overload faults. The SOFT START state is used to black start a PeCo grid. The REGULATE state accomplishes the primary control objective. The SATURATE state indicates that the output limit of the block has been reached. The MPPT state accomplishes the secondary control objective. The control action within each state was tested and validated. An oversupply to the grid during load removal events could not be eliminated completely. However, the response of the MCU to a load removal event was improved compared to the Legacy Grid and able to reduce the oversupply and overcome the shortcoming.

The P&O MPPT algorithm was preferred for the model-based MPPT solution due to its simplicity and ease of execution. To accurately estimate the PV module current,

the current drawn by the control platform was added to the inductor current estimated by the model. A model-based MPPT solution was formulated by replacing the current sensing step in the P&O algorithm with the model. The model-based MPPT was validated to successfully track a MPP.

A PV module was connected to a PeCo grid using the interface developed throughout this research. The PV module and the interface collectively formed a solar GEN block. The GEN block was tasked with charging a battery element of an ES block connected to the grid throughout a day. This emulated the envisioned application of the GEN block under a real-world context. Power supplied by the PV module was successfully used to charge the battery element. The interface developed to connect a PV module to the PeCo grid was validated. Furthermore, the PeCo grid was used as a platform for formulating a model-based MPPT solution that obviates the need for any current sensors in a PV system.

7.2 Answer to Main Research Question

The answers to the research sub-questions have been communicated in previous Chapters. The main research question is answered by consolidating these answers.

"What technological advancements can be made to the Legacy Grid to further the PeCo grid from a conceptual prototype to a viable rural electrification solution?"

Technological advancements to the Legacy Grid included both hardware and software improvements. The Legacy Grid technology validated the PeCo grid concept. Due to the prototype nature of the solution and controlled conditions under which it was tested, it is not a viable rural electrification solution. The size and cost of Legacy Grid's prototype blocks needed to be reduced and the capability extended to interface actual PV, wind and battery elements. This research focused on interfacing a PV module to the PeCo grid and used the Legacy Grid technology as a foundation to build upon.

The Flyback converter from the Legacy grid was adopted and the control platform was advanced from a PLC and PWM IC to a MCU. The design of the Flyback converter was adapted to cater for the MCU. The MCU consolidated the PLC and PWM IC into

a single digital solution and drastically reduced the size of the Legacy Grid technology. The control strategy was modelled as a state diagram and executed by the MCU. This improved the flexibility of the control solution. The control strategy was improved to include MPPT capabilities. A model-based MPPT solution was formulated which obviates the need for a current sensor, reducing the cost of the technology. An actual PV module was interfaced to a PeCo grid.

The combination of the PV module and interface are a PV system and when operated under the context of the PeCo grid are considered a GEN block. Tests conducted on the GEN block validated its operation for the real world application. This makes the GEN block viable as a rural electrification solution.

7.3 Recommendations for Future Research

The interface for a PV module developed in this research is viable for rural electrification. However, there are still improvements that can be made to optimise the technology. Several areas where further work is required were communicated in previous Chapters. This section consolidates all of the future research recommendations made throughout this dissertation.

In Chapter 3 future research recommendations pertaining to improving the design and efficiency of the Flyback converter were made. These include:

- Isolated feedback of the grid voltage to the MCU was achieved using an isolation amplifier. The limited output voltage range of the amplifier reduced the resolution of the feedback signal and the cost of the amplifier does not warrant its use. A recommendation for future research was to develop a cost-effective solution for the isolated feedback that does not reduce the resolution of the feedback signal.
- Under lightly loaded conditions the Flyback converter had low efficiency due to increased switching losses. A recommendation for future research to implement pulse frequency modulation so that the switching frequency of the Flyback converter be scaled down with load demand to increase the efficiency under lightly loaded conditions.
- Two voltage regulators were used on the Flyback converter to supply the MCU, the isolation components and driver IC. The regulators are an inefficient solution

and power is lost due to heat dissipation. A recommendation for future research was to implement an onboard multi-output Flyback converter to replace the voltage regulators and reduce power loss

- A recommendation for future research is to reduce the power loss and improve the efficiency of the Flyback converter.

In Chapter 5 future research recommendations pertaining to the control strategy and the autonomous nature of the blocks on the PeCo grid were made. These include:

- Connecting loads to the grid caused a transient under-supply to the grid. A recommendation for future research is to develop an interface for connecting loads to the grid in a soft start manner.
- A recommendation for future research is to investigate the autonomous nature of the blocks on the grid. If the behaviour of blocks on the grid can be modelled, the response of a block to events on the grid may be predicted. This insight into the autonomous nature may be used to establish the limitations of the PeCo grid.

In Chapter 6 future research recommendations pertaining to the MPPT and the installation of the PV modules were made. These include:

- A recommendation for future research is to implement a variable step MPPT algorithm to reduce the oscillations about the MPP.
- A recommendation for future research is to design a mounting solution for the PV modules interfaced to the grid. If the PV modules are installed on a rooftop, temperature conditions will reduce the power output from the PV module. The mounting solution should take into consideration the rural setting where the PV modules will be deployed and aim to keep the PV modules cool.

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Appendix A

Transformer Losses

When constructing the transformer, power losses are taken into consideration and the choice of materials and method of construction should be aimed at minimising the following: winding loss, core loss and stray loss.

A.1 Winding Loss

The resistance of a conductor is expressed by:

$$R_{con} = \rho_{con} \frac{l_{con}}{A_{con}} \quad (\text{A.1})$$

where:

ρ_{con} = The resistivity of the conductor.

l_{con} = The length of the conductor.

A_{con} = The cross-sectional area of the conductor.

When current flows through a conductor, heat is dissipated due to the winding loss. For a transformer winding loss is expressed by:

$$P_W = I_{con}^2 R_{con} t \quad (\text{A.2})$$

where:

I_{con} = The current flowing through the conductor.

t = The time in seconds that the current is maintained for.

To minimise winding loss the resistance of the conductor used to construct the inductors is taken into consideration. The length of the conductor is kept constant because varying this will alter the number of turns. The resistivity of the conductor can be reduced by using a conductor with a low resistivity such as silver ($\rho_{silver} = 1.59 \mu\Omega/\text{cm}$). However, this will increase the cost of the transformer and copper ($\rho_{copper} = 1.72 \mu\Omega/\text{cm}$) offers a more affordable solution. Thus, in practice only the cross-sectional area of

A.2 Core losses

Core losses are sub-divided into hysteresis losses and eddy current losses and are dependant on the core material and structure. Hysteresis losses arise from the magnetisation and demagnetisation of the core [35, 28] and are expressed by:

$$P_h = \eta B_{max}^n V_{core} \quad (\text{A.3})$$

where:

η = The Steinmetz hysteresis coefficient of the core material.

B_{max} = The maximum flux density.

n = The Steinmetz exponent of the core material.

V_{core} = The volume of the conductor.

From A.3, hysteresis losses are dependant on the choice of core material. Hysteresis losses are minimised by selecting a core material with a low Steinmetz coefficient and exponent or by reducing the size of the core. The magnetic flux produced by the current flowing through the conductors that are wound around the core will, according to Faraday's law, induce current in the core. These currents are eddy currents and the power loss caused by eddy currents in the core are expressed by:

$$P_e = \frac{(\pi B_{max} f \tau_{core})^2}{6 \rho_{core}} V_{core} \quad (A.4)$$

where:

τ_{core} = The thickness of the core.

ρ_{core} = The resistivity of the core material.

Eddy current losses can be reduced by laminating the core. Smaller size core exhibits less eddy current losses. The choice of core material must have a low resistivity.

A.3 Stray loss

Coupling is a measure of the magnetic flux produced by the current flowing through a conductor that links with another conductor. Consider two conductors wound around a core, the coupling coefficient between the conductors is expressed by:

$$k = \sqrt{1 - \frac{L_{short}}{L_{open}}} \quad (A.5)$$

where:

L_{short} = The inductance measured across a conductor with the other conductor shorted.

L_{open} = The inductance measured across the same conductor with the other conductor left open.

The fraction of magnetic flux that does not couple between the conductors is leakage flux. Leakage flux can couple with surrounding materials and induce eddy currents within them. These account for the stray losses of the transformer. Stray losses are minimised by improving the coupling coefficient between conductors and this is dependant on the winding method used.

Appendix B

Flyback Converter Details

Table B.1 Bill of materials.

Reference	Component	Description
U5	Adum3190	Isolation Amplifier
C17	Cap 100uF 25v sm	Capacitor
C20	Cap 100uF 25v sm	Capacitor
C23	Cap 100uF 25v sm	Capacitor
C3	Cap 100uF 25v sm	Capacitor
C7	Cap 100uF 25v sm	Capacitor
C8	Cap 1206	Capacitor
C27	Cap 1206	Capacitor
C19	Cap 1206	Capacitor
C1	Capacitor	Capacitor
C2	Capacitor	Capacitor
C4	Capacitor	Capacitor
C9	Capacitor	Capacitor
C11	Capacitor	Capacitor
C12	Capacitor	Capacitor
C13	Capacitor	Capacitor
C14	Capacitor	Capacitor
C15	Capacitor	Capacitor
C16	Capacitor	Capacitor
C22	Capacitor	Capacitor
C25	Capacitor	Capacitor
C26	Capacitor	Capacitor
C18	Capacitor	Capacitor
C21	Capacitor	Capacitor
PL1	CONN SIL 2	2 way Pin Header
PL2	CONN SIL 2	2 way Pin Header
PL4	CONN SIL 2	2 way Pin Header
PL5	CONN SIL 2	2 way Pin Header
PL6	CONN SIL 2	2 way Pin Header
U2	DC-DC Conv	DC-DC converter
D2	Diode 4007 SM	Diode
D3	Diode trans sm	Diode
T2	E25	Transformer
VR2	IRF3205STRLPBF	MOSFET
J1	Jtag	20-Pin CTI Connector
VR1	L78M12ABDT-TR	12 V Regulator
LED3	LED (3mm)	LED
LED4	LED (3mm)	LED
SW1	Pushbutton	Button

Table B.2 Bill of materials continued.

Reference	Component	Description
R 2	R 0.25W SMTF 1.0K	Thick Film Surface Mount Resistor
R 12	R 0.25W SMTF 1.0K	Thick Film Surface Mount Resistor
R 19	R 0.25W SMTF 10K	Thick Film Surface Mount Resistor
R 17	R 0.25W SMTF 10K	Thick Film Surface Mount Resistor
R 5	R 0.25W SMTF 10K	Thick Film Surface Mount Resistor
R 3	R 0.25W SMTF 10K	Thick Film Surface Mount Resistor
R 24	R 0.25W SMTF 10K	Thick Film Surface Mount Resistor
R 18	R 0.25W SMTF 10K	Thick Film Surface Mount Resistor
R 16	R 0.25W SMTF 10K	Thick Film Surface Mount Resistor
R 8	R 0.25W SMTF 100	Thick Film Surface Mount Resistor
R 4	R 0.25W SMTF 100	Thick Film Surface Mount Resistor
R 11	R 0.25W SMTF 100	Thick Film Surface Mount Resistor
R 7	Resistor	Resistor
R 14	Resistor	Resistor
R 20	Resistor	Resistor
R 23	Resistor	Resistor
R 9	Resistor	Resistor
R 10	Resistor	Resistor
R 13	Resistor	Resistor
R 21	Resistor	Resistor
R 22	Resistor	Resistor
R 6	Resistor power SM	Resistor 20 W
U6	TC428COA	MOSFET Driver
CONN1	Test term	Connector
CONN2	Test term	Connector
CONN3	Test term	Connector
CONN4	Test term	Connector
U7	TMS320F28027PTS	MCU
U1	Voltage regulator	3.3V voltage regulator
D4	VS-MURB2020CTPBF	Diode
ZD3	Zener 15V	Zener Diode
ZD4	Zener 15V	Zener Diode

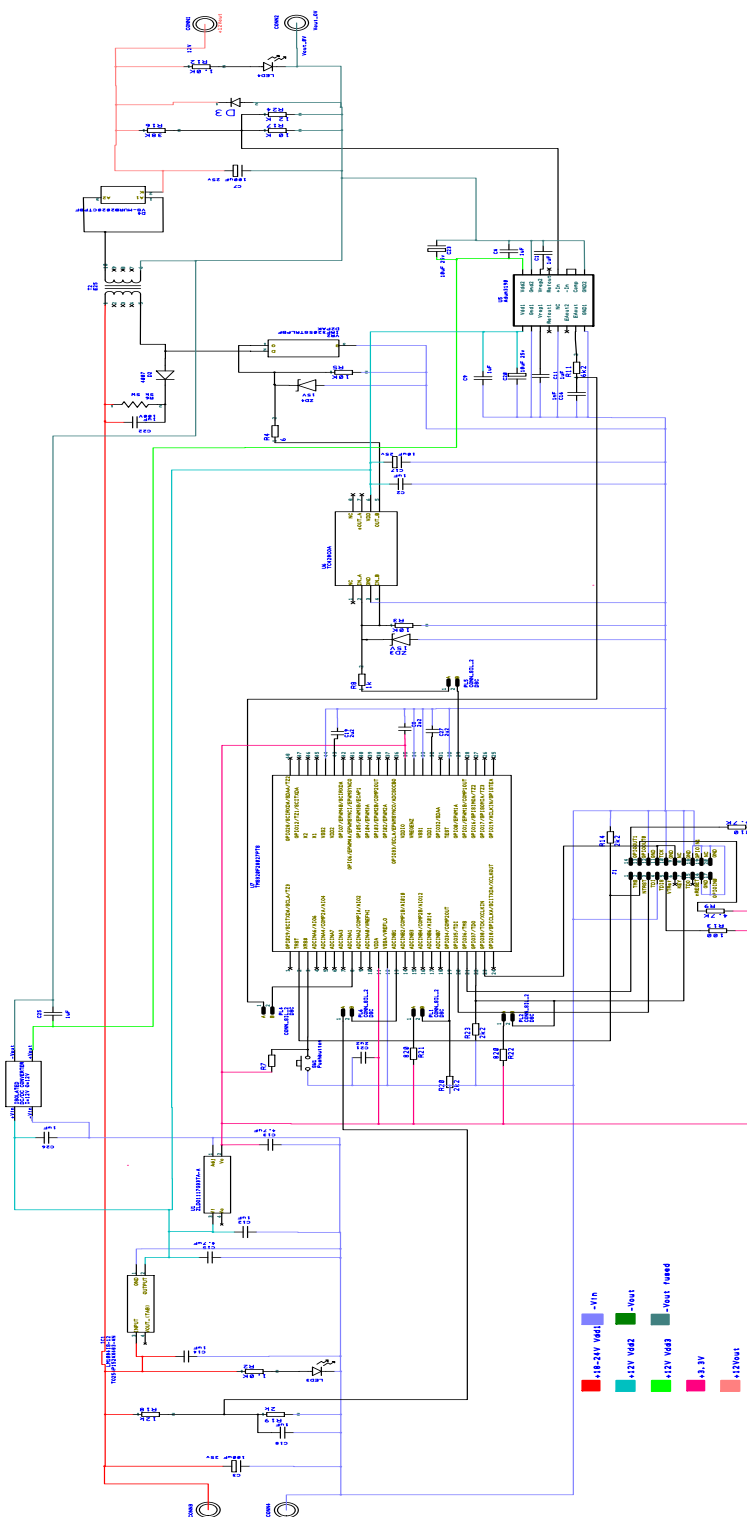


Fig. B.1 Complete schematic of Flyback converter.

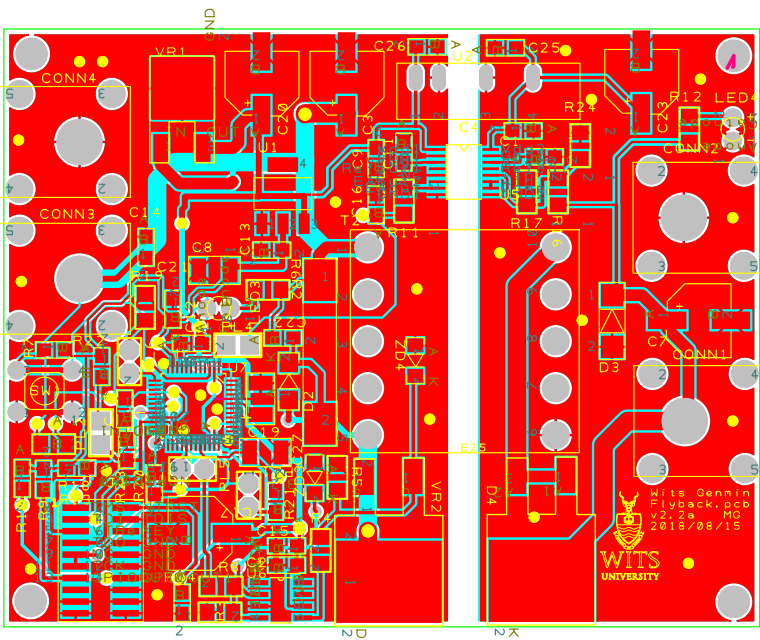


Fig. B.2 Printed circuit board for Flyback converter

Appendix C

Equations

C.1 Covariance

The covariance between two variables gives an indication of their relationship. Positively related variables have a positive covariance. Negatively related variables have a negative covariance. The covariance between two samples of data is calculated using:

$$COV(x, y) = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{n - 1} \quad (C.1)$$

where:

x = The independent variable.

y = The dependent variable.

$\bar{x}$ = The mean of x .

$\bar{y}$ = The mean of y .

n = The total number of data points in the sample.

C.2 Sample standard deviation

The standard deviation is a measure of the variation of the data points about the mean of the data. Standard deviation is calculated using:

$$S_x = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}} \quad (\text{C.2})$$

Appendix D

Loading and Load Removal Results

D.1 Loading Results

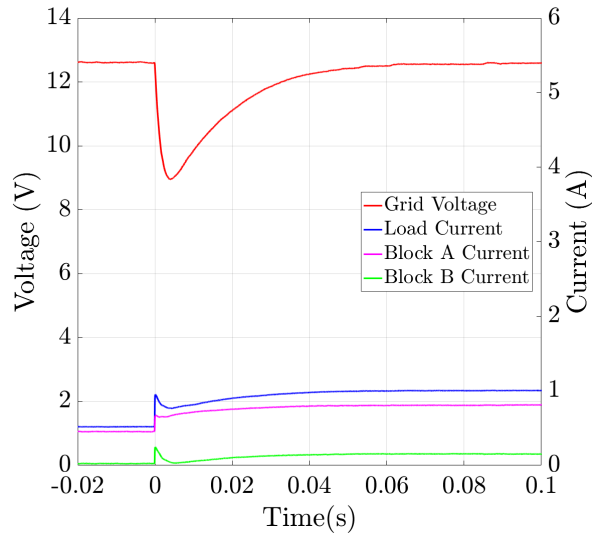


Fig. D.1 $\Delta\text{Load} = 0.5 \rightarrow 1$ A

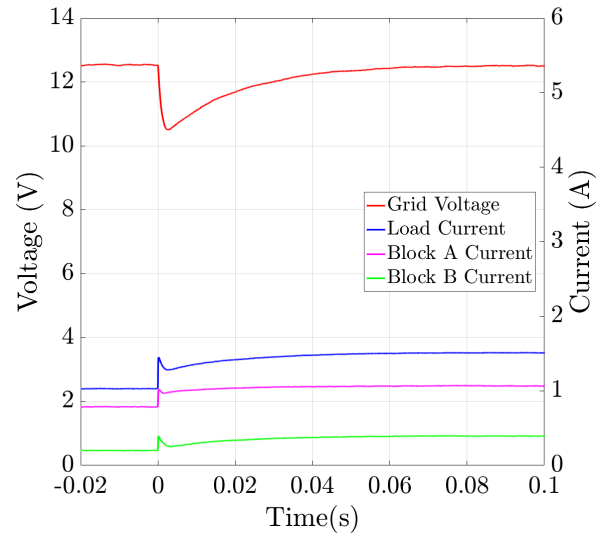
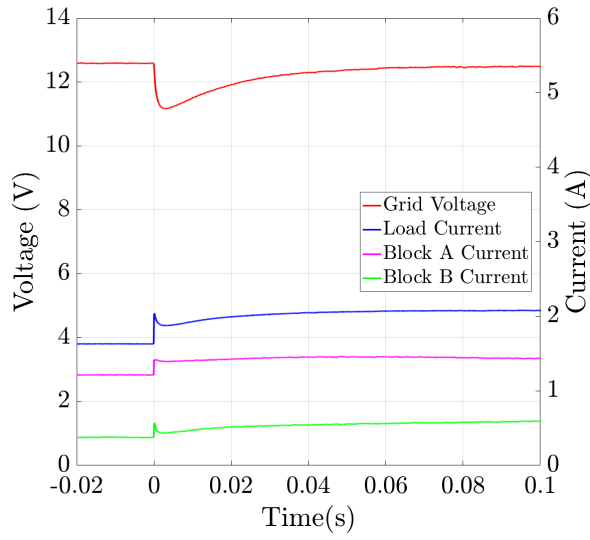
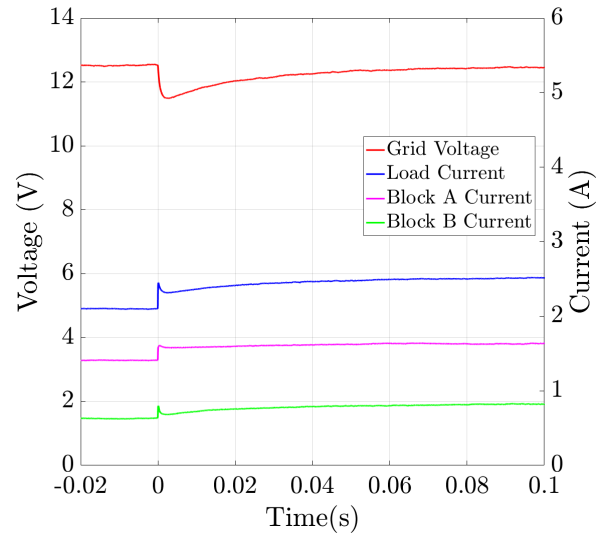
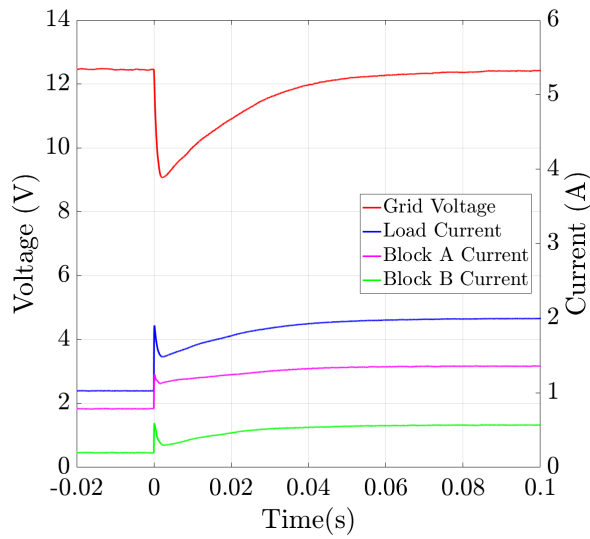
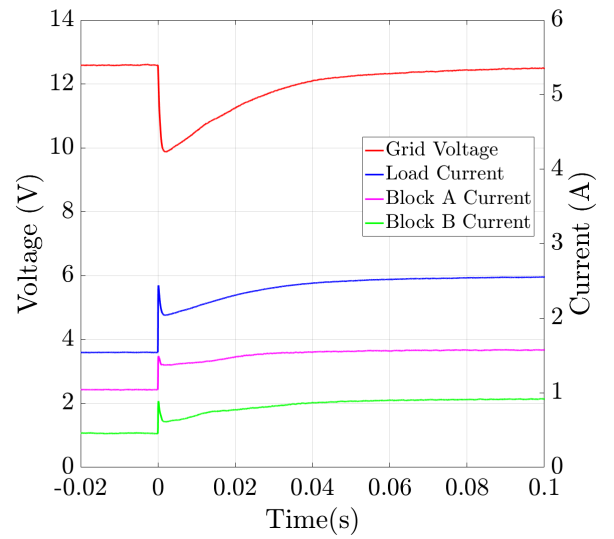
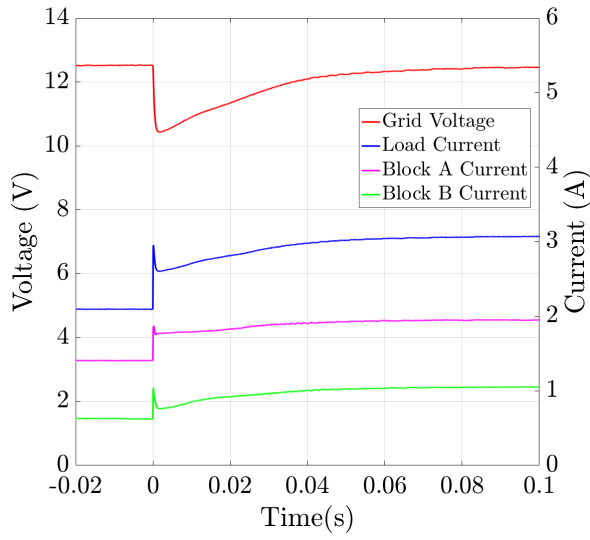
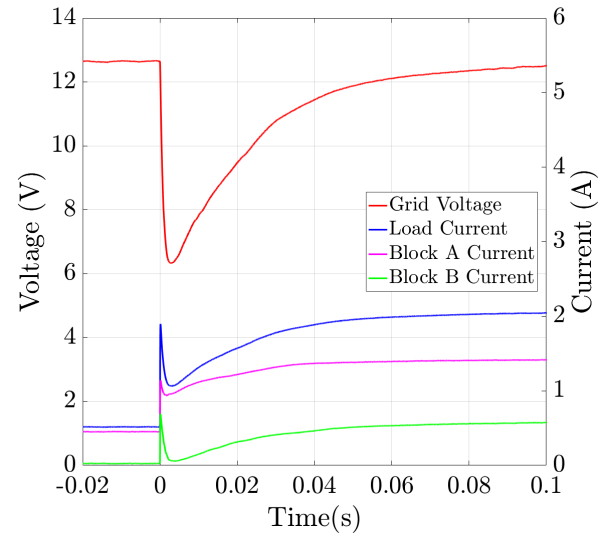
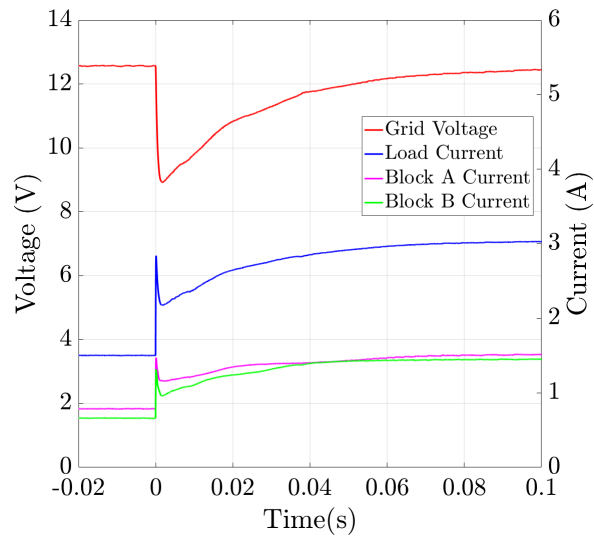
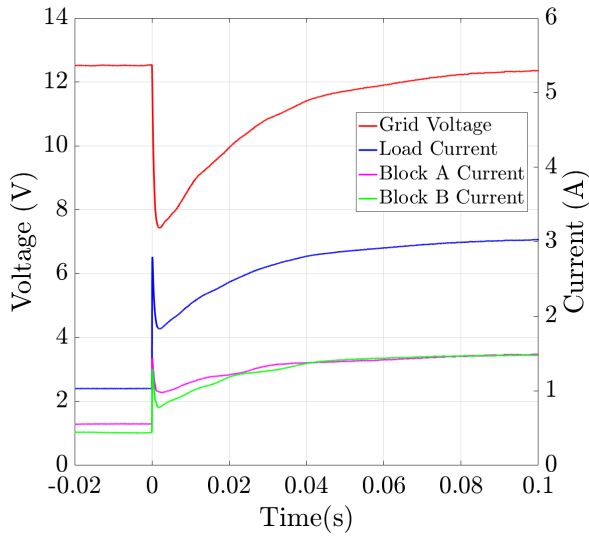
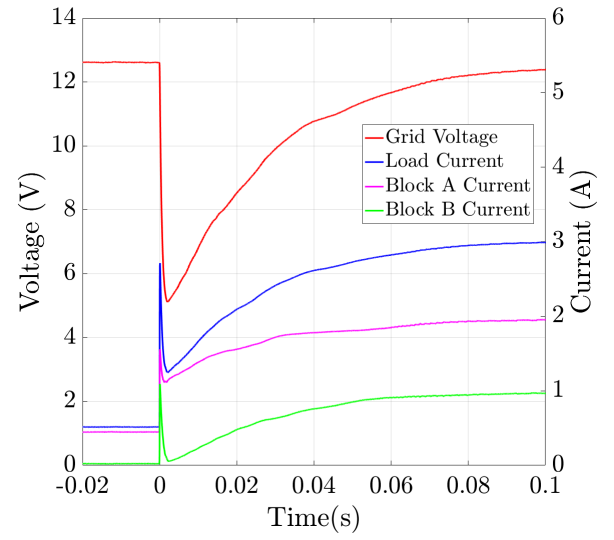


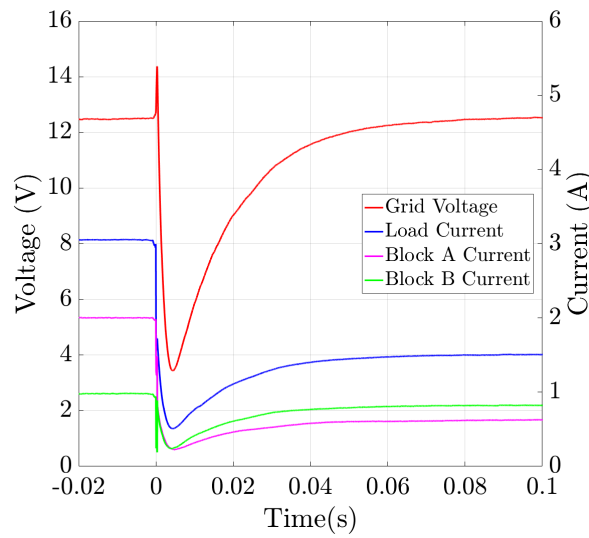
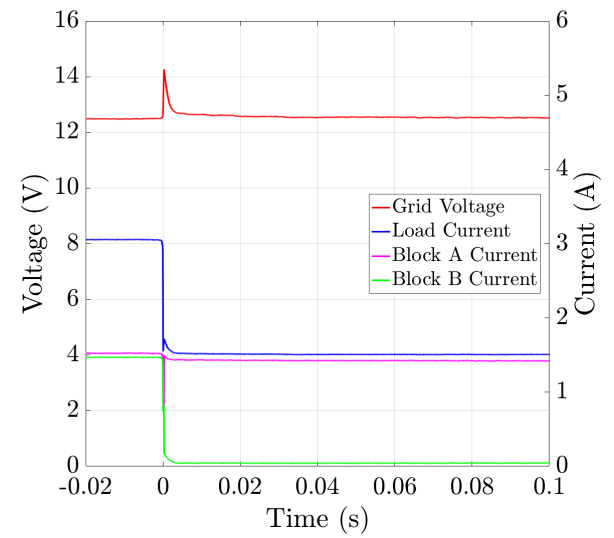
Fig. D.2 $\Delta\text{Load} = 1 \rightarrow 1.5$ A

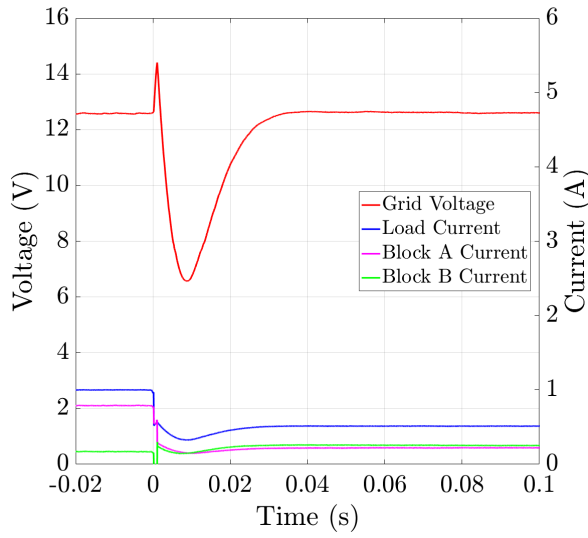
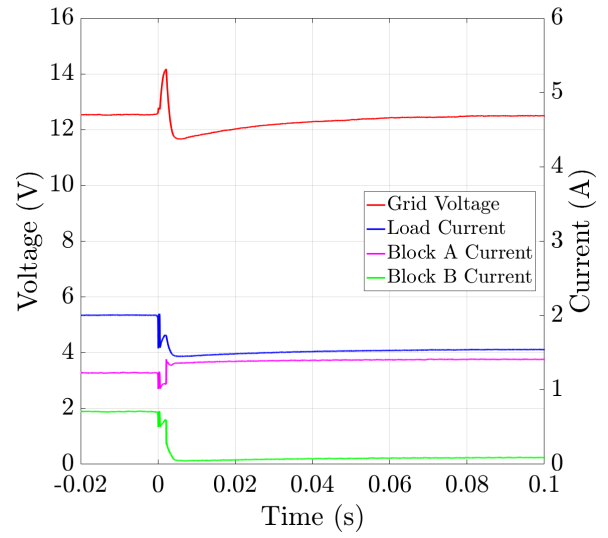
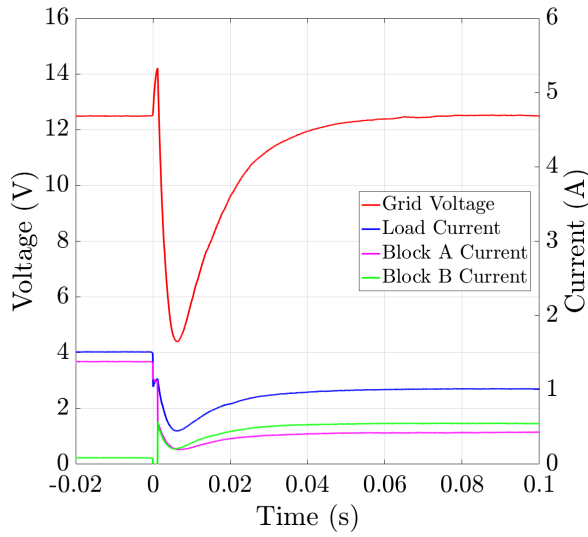
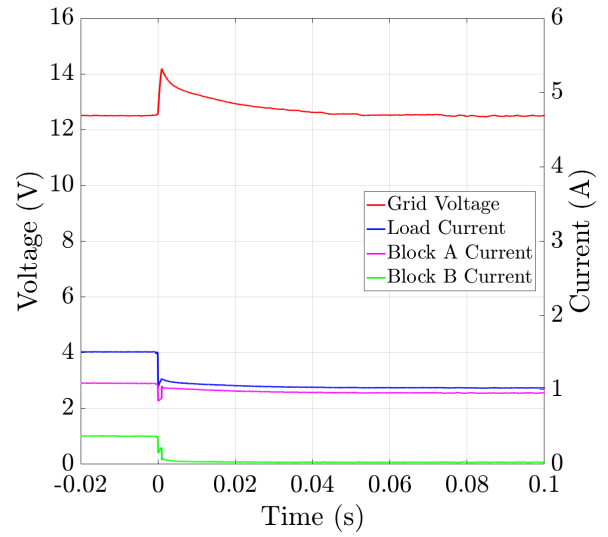
Fig. D.3 $\Delta\text{Load} = 1.5 \rightarrow 2$ AFig. D.4 $\Delta\text{Load} = 2 \rightarrow 2.5$ AFig. D.5 $\Delta\text{Load} = 1 \rightarrow 2$ AFig. D.6 $\Delta\text{Load} = 1.5 \rightarrow 2.5$ A

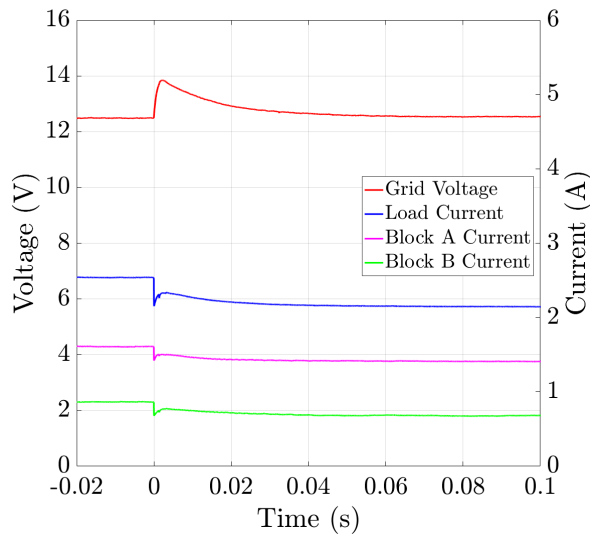
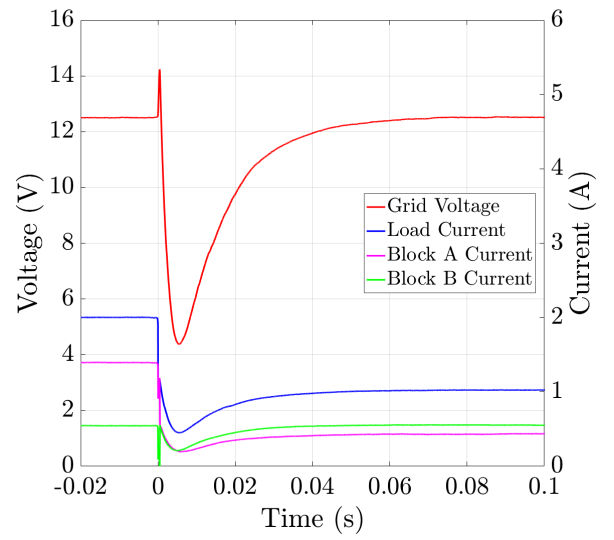
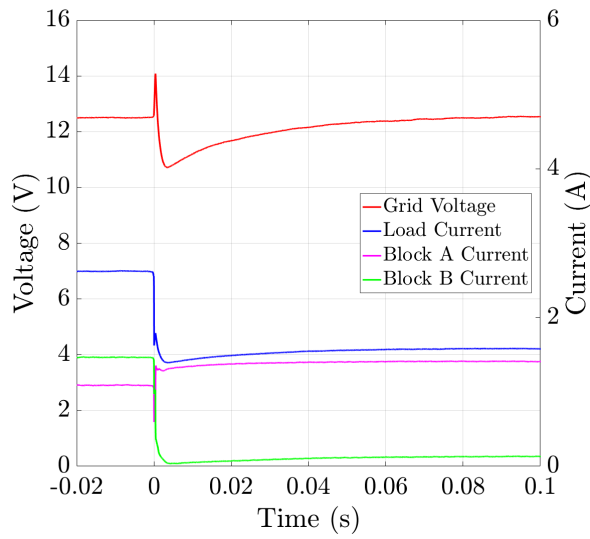
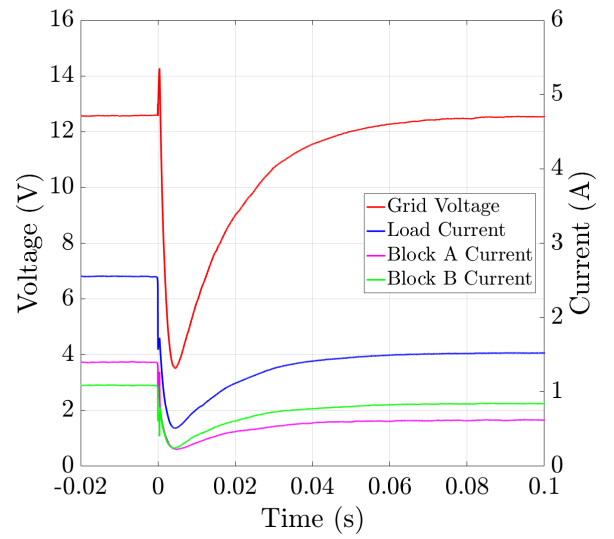
Fig. D.7 $\Delta\text{Load} = 2 \rightarrow 3$ AFig. D.8 $\Delta\text{Load} = 0.5 \rightarrow 2$ AFig. D.9 $\Delta\text{Load} = 1.5 \rightarrow 3$ A

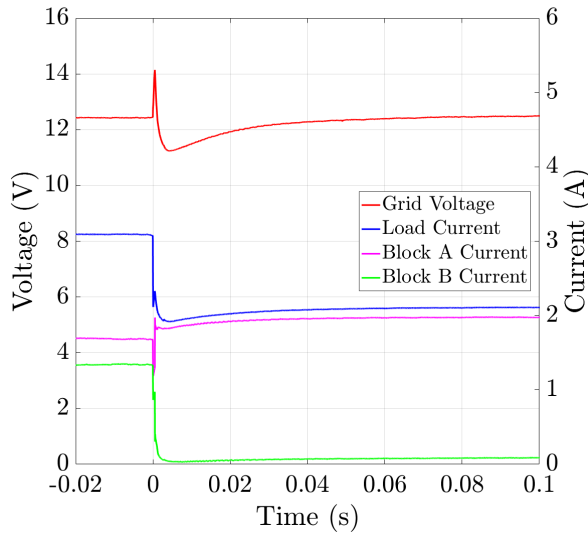
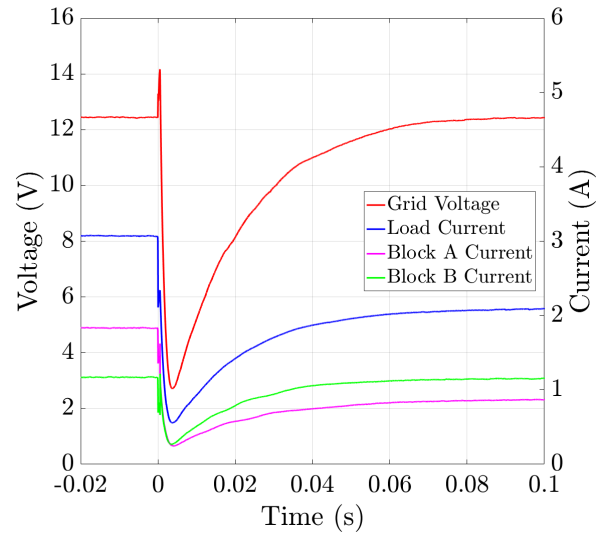
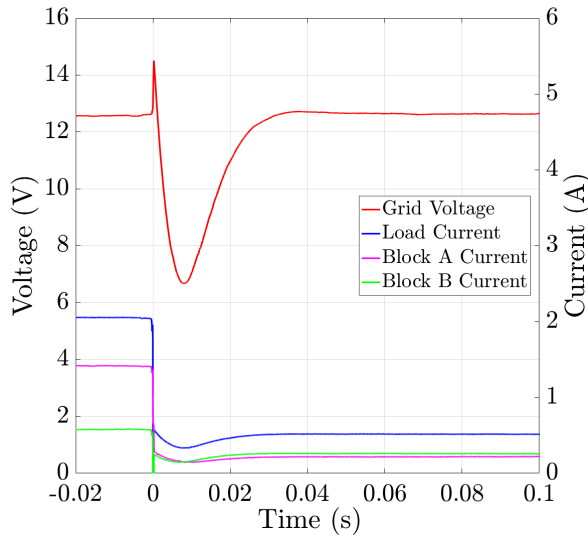
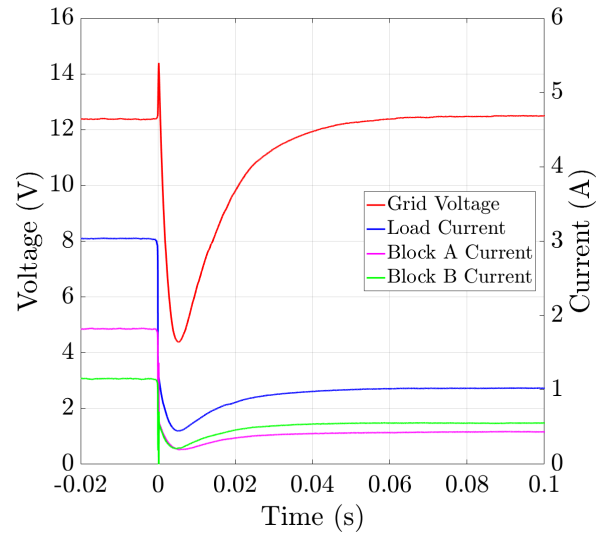
Fig. D.10 $\Delta\text{Load} = 1 \rightarrow 3$ AFig. D.11 $\Delta\text{Load} = 0.5 \rightarrow 3$ A

D.2 Load Removal Results

Fig. D.12 $\Delta\text{Load} = 3 \rightarrow 1.5$ AFig. D.13 $\Delta\text{Load} = 3 \rightarrow 1.5$ A *

Fig. D.14 $\Delta\text{Load} = 1 \rightarrow 0.5 \text{ A}$ Fig. D.15 $\Delta\text{Load} = 2 \rightarrow 1.5 \text{ A}$ Fig. D.16 $\Delta\text{Load} = 1.5 \rightarrow 1 \text{ A}$ Fig. D.17 $\Delta\text{Load} = 1.5 \rightarrow 1 \text{ A}^*$

Fig. D.18 $\Delta\text{Load} = 2.5 \rightarrow 2 \text{ A}$ Fig. D.19 $\Delta\text{Load} = 2 \rightarrow 1 \text{ A}$ Fig. D.20 $\Delta\text{Load} = 2.5 \rightarrow 1.5 \text{ A}^*$ Fig. D.21 $\Delta\text{Load} = 2.5 \rightarrow 1.5 \text{ A}$

Fig. D.22 $\Delta\text{Load} = 3 \rightarrow 2 \text{ A}^*$ Fig. D.23 $\Delta\text{Load} = 3 \rightarrow 2 \text{ A}$ Fig. D.24 $\Delta\text{Load} = 2 \rightarrow 0.5 \text{ A}$ Fig. D.25 $\Delta\text{Load} = 3 \rightarrow 1 \text{ A}$

Appendix E

Flyback Mode of Operation

A Flyback converter was designed to operate in discontinuous conduction mode (DCM). The power output of the Flyback converter is controlled using a proportional control scheme. The duty-cycle (D_{PWM}) of the PWM signal driving the MOSFET is proportionally controlled according to the difference between a set-point voltage and the desired output voltage. The primary and secondary inductor currents, I_p and I_s were measured to verify the mode of operation of the Flyback converter, see Figure E.1.

During turn on, the Flyback converter was observed to be operating in continuous conduction mode (CCM) and boundary conduction mode (BCM) for the first few cycles before stabilising to DCM, see Figure E.2. During turn on, the error between the set-point and desired output voltage is at a maximum for the first cycle and steadily decreases as V_{out} increases. This inherently leads to a large increase in D_{PWM} and current through the inductors for the first few cycles. The inductor saturates during the first few cycles and the Flyback converter is pushed into CCM and BCM. The proportional control coefficient was tuned by following an iterative process to reduce the current during turn on until the Flyback converter was observed to no longer be operating in CCM and BCM, see Figure E.3 and Figure E.4.

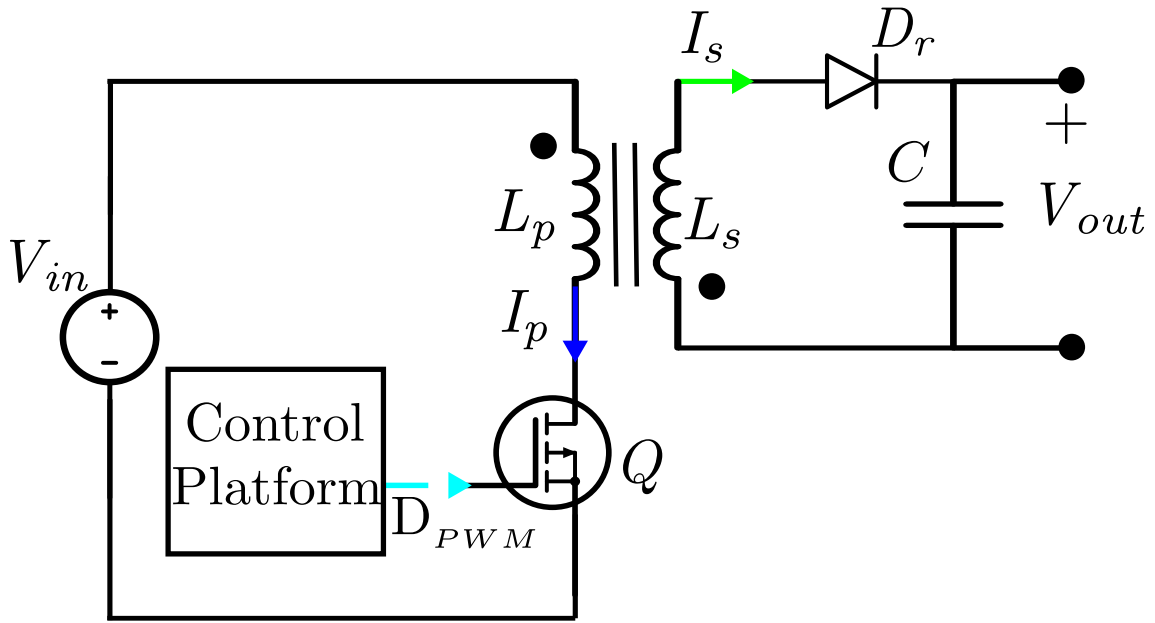


Fig. E.1 Schematic of Flyback converter.

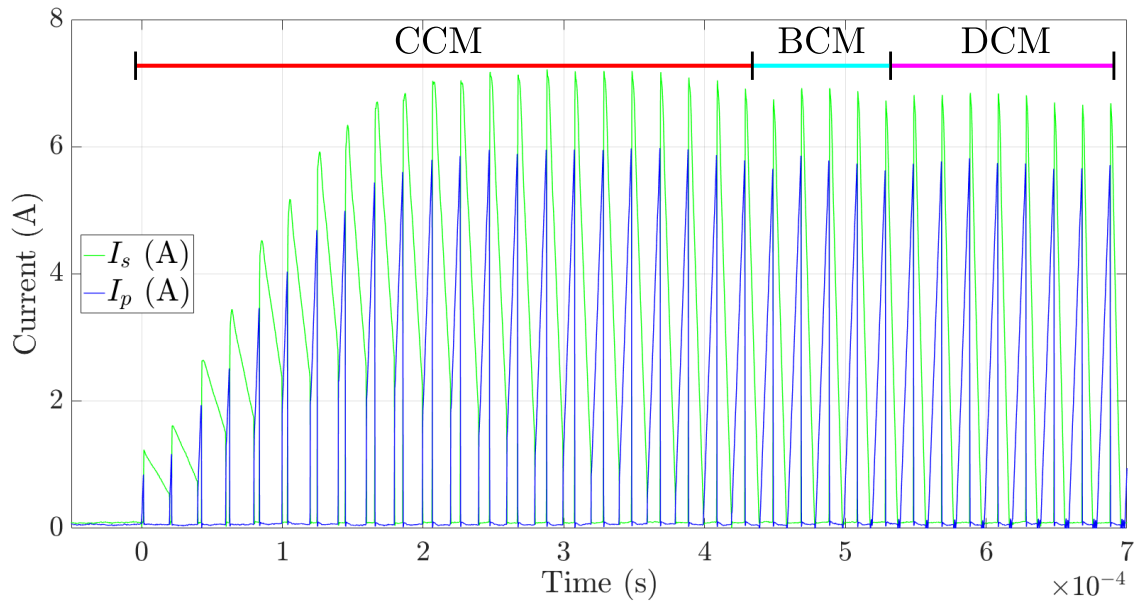


Fig. E.2 Untuned Flyback converter operating in CCM and BCM during turn on.

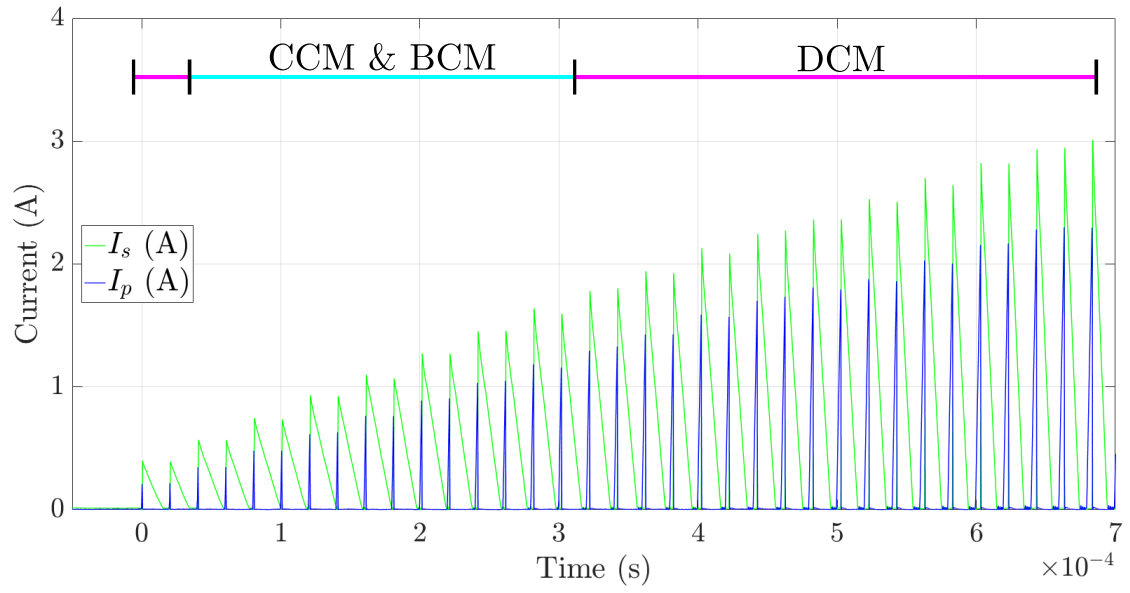


Fig. E.3 Tuning iteration.

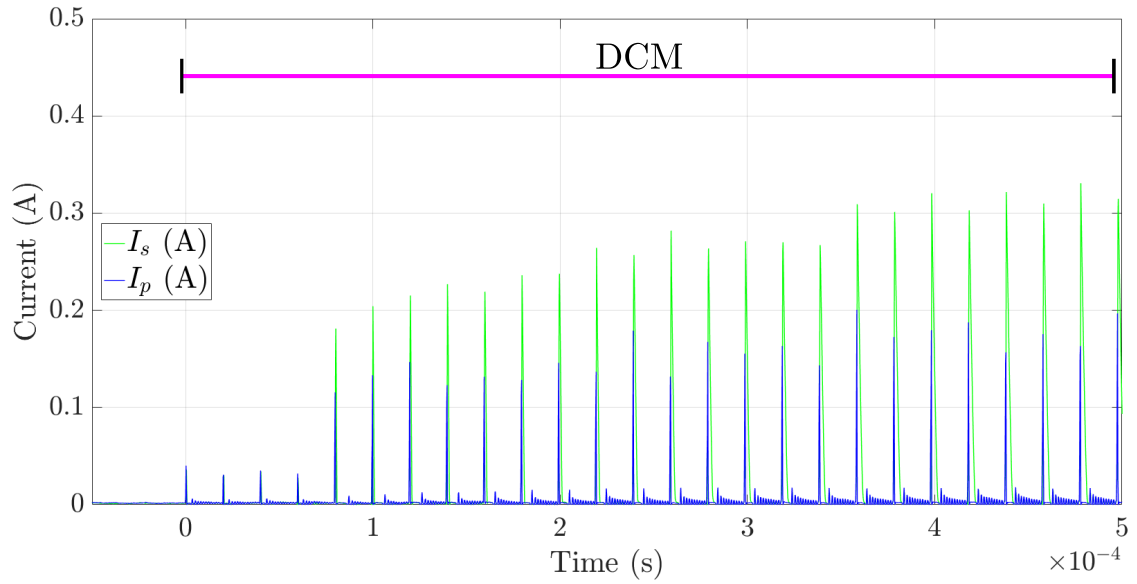


Fig. E.4 Tuned Flyback converter operating in DCM during turn on.

Flyback Converter Controlled by Model-Based Current MPPT for a Photovoltaic Power System

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Abstract—A model is derived to estimate the primary-side inductor current of a discontinuous current mode Flyback converter. The model is validated by comparing the current estimated by the model to the current sensed using a sense resistor. The model was applied in a photovoltaic (PV) system which interfaced a PV module to a battery via a Flyback converter in order to charge a 12V lead acid battery. The system successfully controlled power flow from the PV module according to a model-based current perturb and observe (P&O) maximum power point tracking (MPPT) algorithm.

Index Terms—Flyback converter, inductor, primary-side, non-invasive, sensor-less, maximum power point tracking (MPPT), maximum power point (MPP), photovoltaic (PV), model based, perturb and observe (P&O), discontinuous current mode (DCM)

Work done by [8] highlights the advantages of an ANN based MPPT algorithm over the perturb and observe (P&O) algorithm which are a faster and more precise response under rapidly changing solar irradiation levels and a reduction in power oscillation under constant or slow changes of solar irradiation. However, the use of ANN is computationally burdening, complex and cannot be implemented on a low-cost digital signal processor (DSP) [9]. The simplicity and ease of implementation of the P&O algorithm is why it is one of most common and widely used MPPT algorithms [1], [10]–[14]. Work done by [10] reviews and compares 19 different MPPT algorithms. Current sensing is a requirement for 12 of these algorithms and includes the P&O algorithm.

I. INTRODUCTION

Inductor current-sensing in DC-DC converters is primarily used for over-current protection, current mode control and power management [1]–[6]. In this paper, the application is extended to control power flow from a PV module via a DCM Flyback converter according to a MPPT algorithm in a PV system. A model is derived to estimate the primary-side inductor current of a DCM Flyback converter. The model is validated by measuring the inductor current using a series sense resistor and correlating this to the inductor current estimated from the model. The model is applied in a PV system controlling power flow according to the P&O MPPT algorithm.

II. PV SYSTEMS

The characteristic power curve of a PV module is non-linear and varies with solar irradiation levels and operating temperature, see Fig. 1. Power flow from a PV module is controlled by a MPPT algorithm to track the point at which maximum power is output under varying conditions. Generally, MPPT algorithms require the output current and/ or the output voltage of the PV module to be sensed to determine the PV module power. From this, the algorithm determines which direction to shift the operating point (OP) on the I-V curve to track the MPP: <file:///C:/Users/Raees/Documents/tEx/Paper/Paper.pdf>. There are model-based MPPT algorithms such as the artificial neural network (ANN) MPPT algorithms presented in [7] and [8].

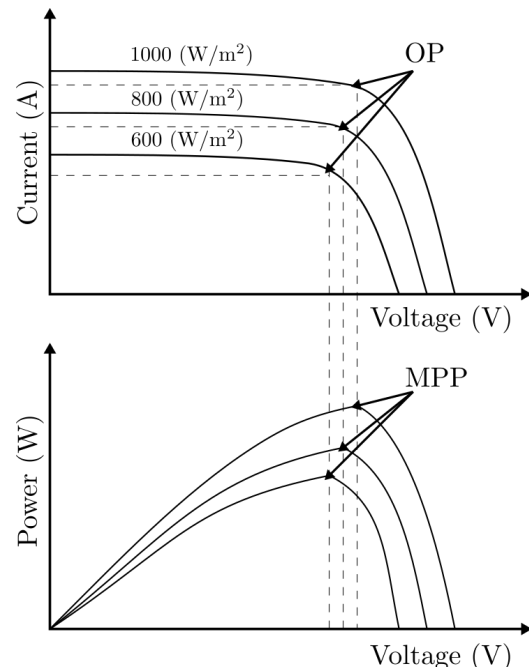


Fig. 1. I-V and characteristic power curve of a PV module.

III. INDUCTOR CURRENT-SENSING IN DC-DC CONVERTERS

Fig. 2 depicts a PV module connected to a Flyback converter. The PV module current can be determined by sensing the primary-side inductor current. A conventional technique is to place a sense resistor in series with the inductor and the voltage drop created across the resistor is indicative of the inductor current according to Ohm's law. The power loss of this technique is a major drawback. Thus, other techniques that have been developed are categorised as loss-less techniques as no additional sensing resistor is added to the current path [7]. Examples of loss-less techniques and their application are discussed by [1], [2], [5], [6].

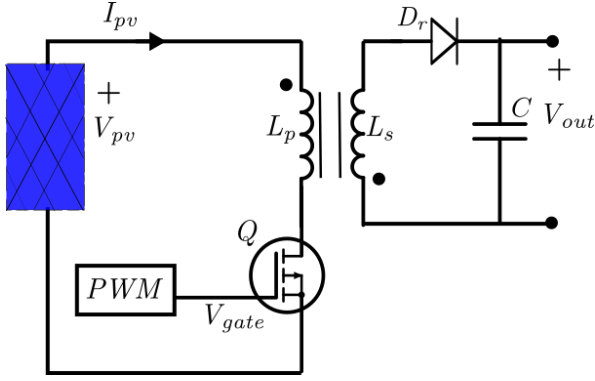


Fig. 2. Schematic of a PV module connected to a Flyback converter.

A. Observer-based technique

The observer-based technique presented by [3], does not require a physical sensor. The premise for observer-based techniques is to create a model of the system from knowledge of the relationship between system parameters and their state. This is advantageous over other techniques as it is non-invasive. Consider the voltage-current relationship of an inductor:

$$V(t) = L \times \frac{dI}{dt} \quad (1)$$

where V is the voltage across the inductor, L the inductance and dI/dt the rate of change of current with time. By integrating (1) the inductor current can be estimated if the inductance is known:

$$I = \frac{1}{L} \int_0^t V(t) dt \quad (2)$$

Work done by [3] discusses the use of an observer-based technique to derive a model based on (2) to reconstruct the inductor current from the inductor voltage. A model is derived for several topologies of DC-DC converters except the Flyback topology.

IV. MODEL DERIVATION

The Flyback converter, see Fig. 2, is an isolated converter. The winding of the primary and secondary inductors, L_p and L_s are opposing. The Flyback operates in an alternating ON and OFF state determined by the MOSFET (Q) switched by the PWM signal. The Flyback circuit during the ON and OFF state is depicted by Fig. 3 and the waveforms describing the operation of the Flyback in DCM is depicted by Fig. 4. Power flow is controlled by adjusting the PWM duty-cycle D .

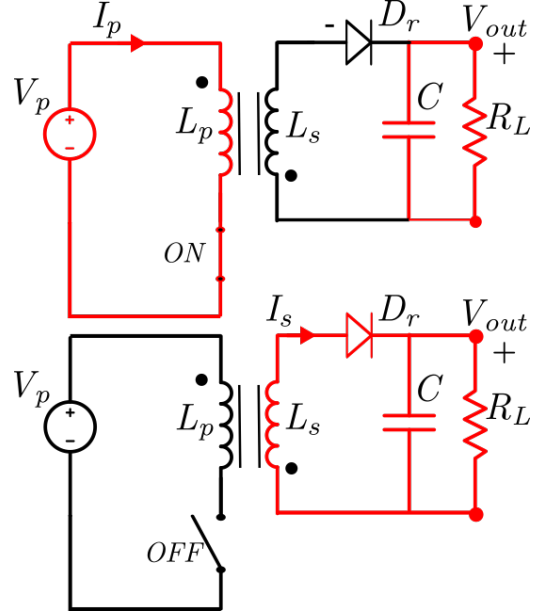


Fig. 3. Schematic of the Flyback circuit during the ON and OFF states.

During the ON-state the source voltage V_p is applied across L_p . The primary-side current I_p flows through L_p and rises linearly from zero to a peak value I_{pk} over the ON time period t_{on} . The value of I_{pk} is derived from (2) and is expressed by (3). Energy is transferred from V_p and stored in L_p . The Diode D_r does not conduct during t_{on} .

During the OFF-state, D_r conducts and the stored energy is delivered from L_s to the output capacitor C which delivers to the load R_L . The secondary side current I_s decreases linearly from I_{pk} to zero during the time period t_{off} .

The ON time period is expressed in terms of the PWM duty cycle and switching period T by (4). The average input current during the ON state I_{ave} , is expressed by (5). Equation (5) reduces to (6) since the waveform is triangular in shape. From (3), (4) and (6), the average current flowing through the primary-side inductor of a DCM Flyback converter can be reconstructed from the source voltage, PWM duty-cycle, switching period and primary-inductance by (7).

$$I_{pk} = \frac{V_p \times t_{on}}{L_p} \quad (3)$$

$$t_{on} = D \times T \quad (4)$$

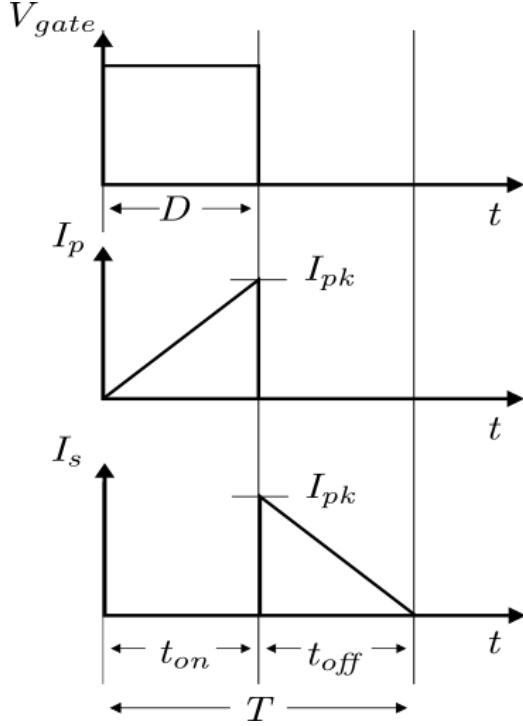


Fig. 4. Key waveforms of a DCM Flyback converter.

$$I_{ave} = \frac{1}{T} \int_0^{t_{on}} i(t) dt \quad (5)$$

$$I_{ave} = \frac{D \times I_{pk}}{2} \quad (6)$$

$$I_{ave} = \frac{V_p \times D^2 \times T}{2 \times L_p} \quad (7)$$

V. FLYBACK CONVERTER

A Flyback converter was built to validate (7), see Fig. 5. The design parameters of the Flyback converter are given in Table I. The Flyback converter has an on-board DSP which generates a PWM signal to drive the MOSFET and controls the power flow by adjusting the duty-cycle. The power output and efficiency of the Flyback converter was determined using the circuit depicted by Fig. 6. A DC power supply, V_s , was connected at the input of the Flyback converter. A 12V lead acid battery, V_{bat} , was connected at the output of the Flyback converter as a sink for the output power. This allowed for output power to be varied without the need to vary a load. The duty-cycle was incremented in steps of 0.5% up until 50% and the input and output power logged. The Flyback converter was able to output 40W at an efficiency of 73%, see Fig. 7. Under lightly loaded conditions, less than 8% duty-cycle, the average efficiency of the Flyback converter is low, 40%. This is due to the power loss from the voltage regulators for the DSP. Above 10% duty-cycle the average efficiency is 74%.

TABLE I
DESIGN PARAMETERS OF FLYBACK CONVERTER.

Parameter	Value
Power	40W
Frequency	50kHz
Efficiency	80%
L_p	20μH
L_s	10μH
Core	E25
Turns ratio	1.36

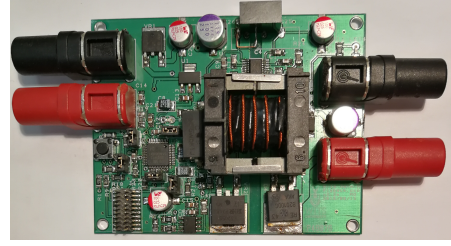


Fig. 5. Flyback converter built to test and validate the model.

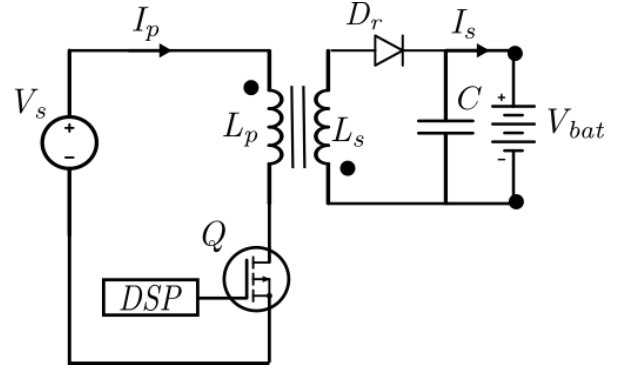


Fig. 6. Schematic of circuit used to determine the power output and efficiency of the Flyback converter.

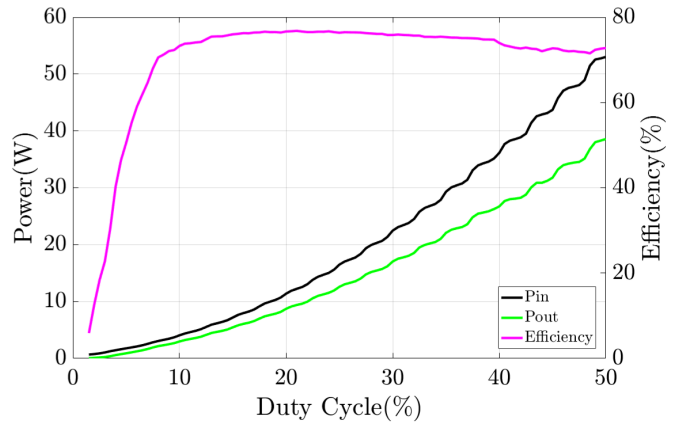


Fig. 7. Efficiency and power of Flyback converter versus duty-cycle.

TABLE II
PARAMETERS OF THE SLP030-12U PV MODULE.

Parameter	Value
Maximum power (P_{max})	30W
Voltage at P_{max} (V_{max})	17.2V
Current at P_{max} (I_{max})	1.74A
Open-circuit voltage (V_{oc})	21.6V
Short-circuit current (I_{sc})	1.93A

VI. MODEL VALIDATION

The circuit depicted by Fig. 8 was built to correlate the current sensed using a 10Ω , 20W series sense resistor to the current estimated by the model, (7). The DSP senses the voltage across the sense resistor V_{sense} and calculates the current according to Ohm's law. The DSP senses V_s and calculates the current according to (7). V_s is kept constant and the duty-cycle increased from 0 to 45% in steps of 0.5%. A 12V lead acid battery V_{bat} was connected at the output of the Flyback to act as a sink for the output power and obviate the need for a variable load.

A. Validation Results

Fig. 9 correlates the current measured from the sense resistor to the current estimated from the model at various duty-cycles. The correlation coefficient between the sensed and estimated current is: $r = 0.9998$. The correlation above 35 % duty cycle drops to: $r = 0.9974$. This is caused by the increase in temperature of the sense resistor due to the increase in power dissipated. At high temperatures, the resistance of the sense resistor increases and this decreases the accuracy of the measurement. The overall strong correlation of the estimated current to the sensed current validates the model.

VII. MODEL APPLICATION

A PV module was interfaced via the Flyback converter to a 12V lead acid battery, see Fig. 10. The PV module parameters are given in Table II. This system tests the control of the power flow from the PV module. Two systems were built to compare the power flow control of a system with MPPT to a system without, see Fig.11. Power flow is controlled by sensing the battery voltage V_{bat} . If the battery voltage is less than the charged level V_c , system-one performs MPPT whereas system- two will increase the duty-cycle up until the maximum D_{max} . Once the battery is charged the system will shut down by setting the duty-cycle to zero.

A. P&O MPPT

Power flow is controlled according to the P&O MPPT algorithm. The P&O algorithm is an iterative approach to finding the MPP by perturbing the duty-cycle to shift the operating point of the system on the characteristic power curve of the PV module [12], [13]. Fig. 12 illustrates the methodology of the P&O algorithm on the characteristic power curve of a PV module.

Fig. 13 depicts the block diagram of the P&O MPPT algorithm. The algorithm senses the PV module current I_{pv} and

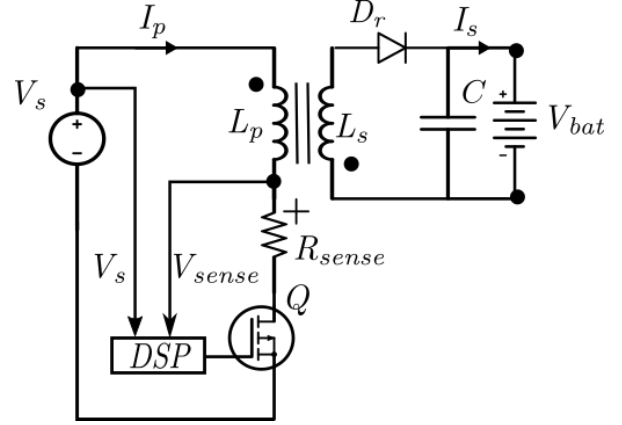


Fig. 8. Schematic of the model validation circuit.

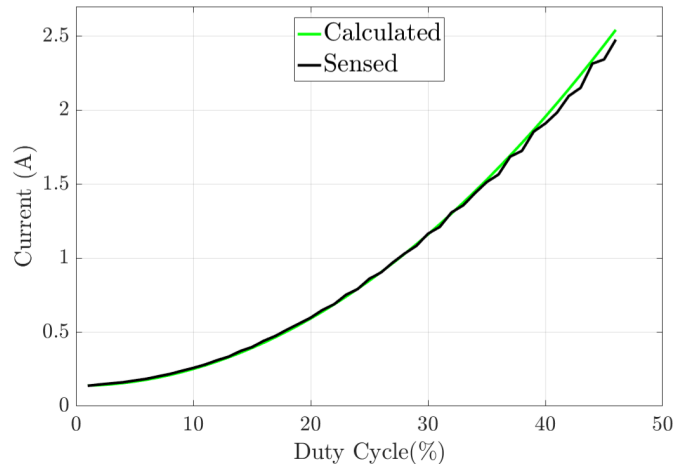


Fig. 9. Correlation of the current sensed and the current estimated.

voltage V_{pv} in order to calculate the PV module power P_{pv} . The change in power and voltage, dP and dV , are determined by comparing the power and voltage at an instant in time $P_{pv(n)}$ and $V_{pv(n)}$ to the power and voltage from the previous instant in time, $P_{pv(n-1)}$ and $V_{pv(n-1)}$. If $dP/dV > 0$ then the operating point is in the region to the left of the MPP and the next perturbation must be positive (decrease PWM duty-cycle). If $dP/dV < 0$ then the operating point is in the region to the right of the MPP and the next perturbation must be negative (increase PWM duty-cycle). If $dP/dV = 0$ then the operating point is at the MPP. In this system only the PV module voltage

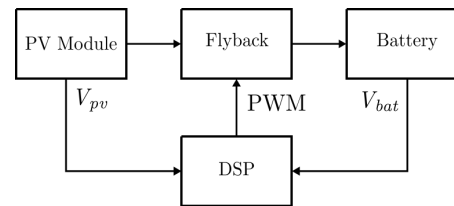


Fig. 10. Block diagram of PV system.

is sensed and (7) is used to estimate the PV module current from the PV module voltage. No invasive or external sensor is required to sense the PV module current.

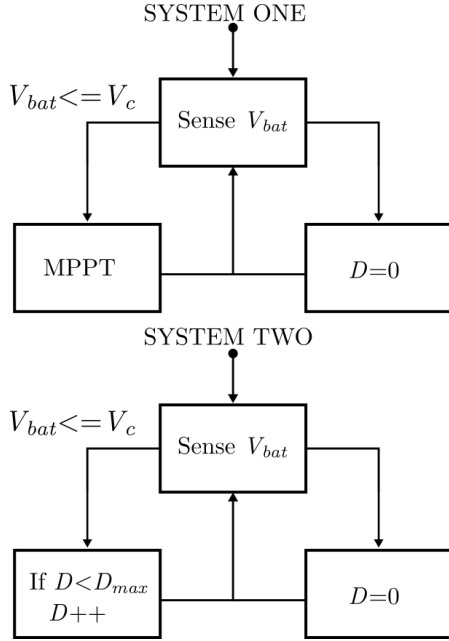


Fig. 11. Block diagram of the power flow control in the systems.

B. Testing and Results

The PV systems were tested over a 24 hour period. V_{pv} , and I_{pv} was logged. P_{pv} and the cumulative energy harvested, E_{cum} was calculated from this data and the results are presented by Fig. 14. Testing commenced at 3pm on day one, indicated by the initial energy harvested. Sunset was at 5pm and there is no increase in energy harvested throughout the night indicated by the flat line of the energy trace. The cumulative energy harvested increases at sunrise on day two at 7am until 3pm on day two when the test is concluded. The total energy harvested was: $E_{s1} = 56424\text{J}$ and $E_{s2} = 46725\text{J}$ for system-one and system-two respectively. Over the 24 hour period, system-two harvested 82% of what system-one did. The MPPT algorithm was thus able to successfully utilize the model to estimate the PV module current. The control of power flow in system-one outperformed system-two.

VIII. CONCLUSION

The need for a MPPT algorithm to control the power flow in PV systems is due to the non-linear characteristic power curve of a PV module. Most MPPT algorithms require the PV module current to be sensed. A model was derived to estimate the primary-side inductor current of a DCM Flyback converter. A test was performed to compare the model-based technique to the conventional, sense resistor technique and there was a strong correlation between the two techniques. A PV system was built to highlight an application of the model. The PV module current was estimated by the model to create a

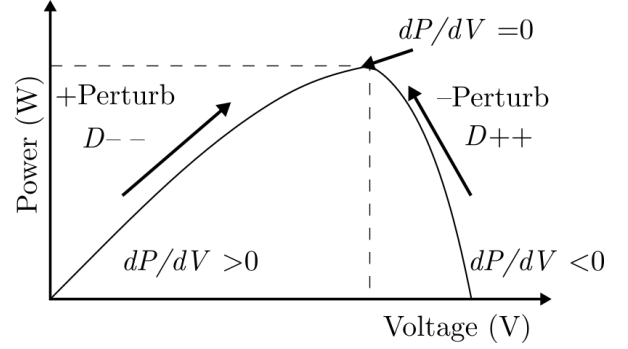


Fig. 12. Methodology of the P&O MPPT algorithm.

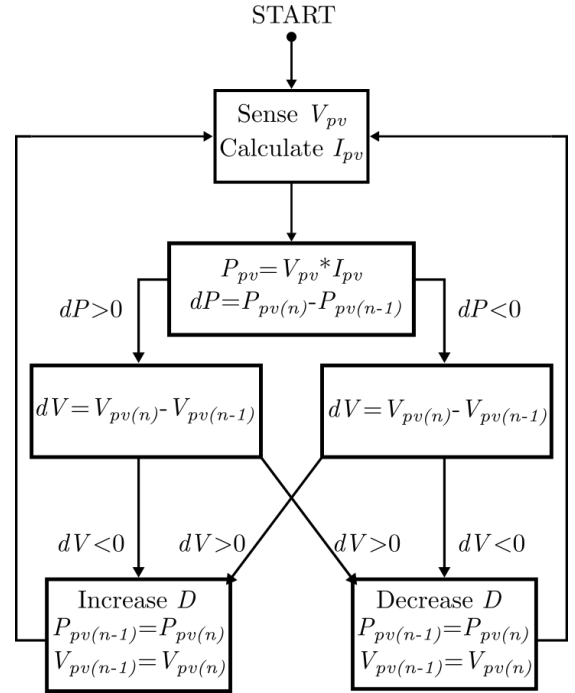


Fig. 13. Block diagram of the P&O MPPT algorithm.

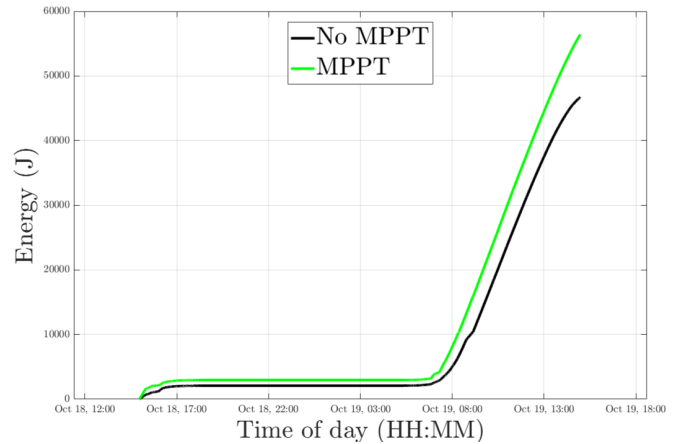


Fig. 14. Comparison of the cumulative energy harvested over a 24 hour period by system-one with MPPT and system-two without MPPT.

model-based current P&O MPPT. The system was tested over 24 hours and the energy harvesting capabilities of the system determined and compare to a second PV system without MPPT capabilities. The system was able to implement the model-based current MPPT and outperformed the system without MPPT by harvesting more energy over the 24 hour period. The system harvested a total of 56424J.

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A Standalone Personal Consumer Grid for Rural Household Electrification

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Abstract—An off-grid, DC, distributed generation smart grid termed the Personal Consumer (PeCo) Grid is proposed as a possible solution to address the energy poverty crisis within rural regions. The PeCo grid utilises a nature inspired de-centralised control strategy and operates at a voltage of 12 V. The PeCo grid is composed of blocks of which there are 3 variants: Renewable energy source blocks, energy storage blocks and load blocks. The flexible architecture of the PeCo grid allows for blocks to be added or removed in a plug-and-play manner. Blocks commission and operate autonomously and bus voltage signalling based control is applied to achieve the required action form each block. The PeCO grid operates autonomously and the end-user requires no technical knowledge to commission or operate the system.

Index Terms—Personalized consumer grid, distributed grid, de-centralized control, bus voltage signalling, autonomous, block, target communities, target families

I. INTRODUCTION

In this paper, a power system for rural community and household electrification is proposed as a possible solution for the energy poverty crisis in rural regions. A background on the energy poverty crisis is given followed by a review on distributed grids. The power system is then introduced as the Personal Consumer grid. The legacy and operation of the power system is discussed followed by a a discussion on how this system could be deployed and distributed to the end user. Lastly, the possibilities of how this system could enhance rural communities and improve the livelihood of end users is discussed.

II. BACKGROUND

The year is 2018 and the human race is in a state of severe energy poverty. There are 1.1 billion people, approximately 16% of the human race, who live off-grid and rely primarily on the use of burning biomass for energy production. The population of countries in sub-Saharan Africa and developing Asia account for 95% of this number and live predominantly in rural areas. These regions in Africa have no existing infrastructure for a utility grid and Africa is one of the least electrified continents in the world. Electrification of these rural areas require innovative solutions to be adopted.

Currently centralized generation systems serve as the primary electrification solution in most regions of the world.

Power is generated from coal, hydro or nuclear energy at large scale electrical power stations away from the point of use. Power is then transmitted through a network of high voltage transmission lines to the eventual load [1] [2]. An advantage of centralised generation is the high energy capability. However, it requires a large capital contribution and interminable construction and maintenance. Thus, it is highly unlikely that a centralized generation system can address the energy poverty crisis.

There has thus been a rise of interest in off-grid, DC distributed generation smart grids incorporating renewable energy sources (RES) and energy storage (ES) as a more pragmatic solution. The energy capability of these systems is less than that of a centralized system. However, these systems generate power at the point of use, require minimal start-up capital and no large scale infrastructure for transmission is required which allows for rapid deployment. The use of RES further addresses the issue of limited quantities of fossil fuel availability and the adverse environmental effects caused by their use. The limited quantities of fossil fuels and its depletion has resulted in a constant rise in the cost of fossil fuel based energy. In contrast, solar energy has been experiencing a price reduction due to increased popularity [3]. This continued cost reduction makes a strong argument for newly developed electrical power systems to utilize RES.

To ensure the success of a new electrification method, it is important that the electricity requirements of the target family are identified. The ESMAP Multi-Tier Framework defines several Tiers of electricity access for households. Tiers are quantified by rated power and energy deliverance, see Figure 1. The minimum required performance of the proposed solution is to be able to provide Tier 2 electricity access for a low energy use family and have the following capabilities:

- Minimum power production of 200 Wh/day or 50 W peak power.
- Minimal power availability from the grid of 4 hrs/day and 2 hrs/night.
- Lighting and phone charging.
- Enhance the productivity of the rural household.

An off-grid, DC distributed generation smart grid solution will be able to meet the minimum required performance and

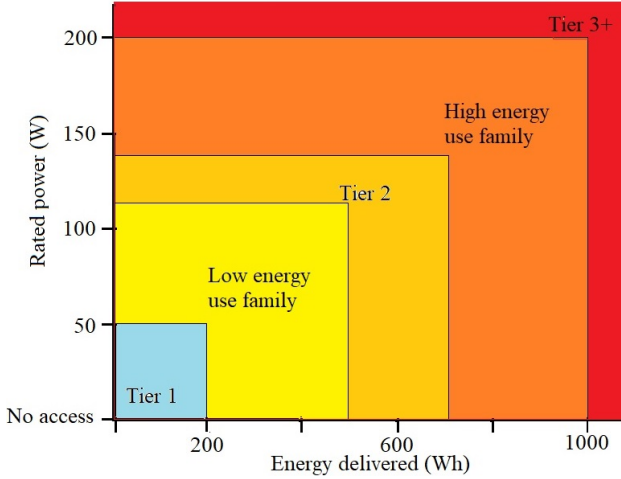


Fig. 1. ESMAP multi-tier framework for energy usage.

due to scalability, eventually grow to provide electricity access for a Tier 2 high energy use family and have expanded capabilities.

III. DISTRIBUTED GRIDS

A. Power generation

Power generation in distributed grids can be solar based [7], [8], wind based [5], [6] or a hybridization of the two and include hydro generation [9]–[13]. A hybrid system creates a more consistent generation profile compared to a single sourced system because the time varying nature of solar and wind power provides an inconsistent yield. This may be overcome by adding storage to stabilize the power system [10], [16]–[20].

B. Topologies

The topology of a distribution grid may be off-grid [16], [21], [22] or grid-tied to a traditional utility grid [9], [10], [23]. Grid-tied systems depend on the utility grid to provide energy shortcomings of the renewable sources. In comparison, off-grid systems must operate on a standalone basis. Due to the lack of utility grid infrastructure in rural regions, off-grid systems are preferred and are capable of operating on either AC [24]–[27] or DC [10], [23], [28], [29].

C. Existing solutions

A Nanogrid or Picogrid is a low power low voltage standalone DC distributed grid. [7], [35]–[38]. The power rating of these grid's are lower than that of the more commonly known Microgrid. The target use for a Nanogrid or Picogrid is a single building or household. Nanogrid technology is capable of meeting the minimum required performance.

A Nanogrid system consists of generation, storage and load elements. Cluster-based Nanogrids [7], [8], [39] create a cluster of elements located within a single building. The cluster is interconnected to neighbouring buildings which also contain a cluster. This interconnection of multiple clusters creates a

power-sharing network that results in a more diverse power system compared to a single Nanogrid.

D. Control architecture

Distributed grids may utilise a centralised or a de-centralised control architecture for grid regulation [30]. A centralised architecture requires a central controller to control all elements of the grid at a global level and thus requires communication links between elements and the controller. A de-centralized architecture eliminates the need for a central controller and communication links and control is deployed locally at elements on the grid. Control architectures may be combined to form a hybrid architecture which employs fast local control at elements and slower global control from a central controller.

An autonomously controlled grid has a decentralised control architecture with no dedicated communication link [28]. Bus voltage signalling is utilised instead of a dedicated communication link as shown in [10]. Bus voltage signalling makes use of the grid voltage to infer information regarding the state of the grid. The inferred information is used to implement the relevant control actions making the grid voltage the information carrier and single shared variable amongst elements on these systems.

Reference [41] evaluates 67 published control strategies for distributed grids using the standardised scoring index developed in [42], [43]. The goal of the work conducted by [41] was to ascertain if these systems are suitable for end user deployment. The conclusion from the conducted study is that none of the current strategies meet the minimum required ratings to be classified as "ready for end-user deployment".

IV. PERSONAL CONSUMER GRID

The Personal Consumer (PeCo) grid is a 12 V distributed DC grid designed for the electrification of single rural households in Africa. The 12 V system leverages on the abundance of currently manufactured household appliances that have been developed for camping and recreational vehicles. The appliances are intended to operate on a 12 V lead acid battery for use in off-grid locations.

Fig. 2 illustrates the basic model of the PeCo grid. The Generation block produces and supplies electricity from a RES to the grid. The ES block charges batteries when the grid load demand is met and there is a surplus of energy production from Generation blocks. When Generation blocks cannot meet the grid load demands, ES blocks discharge batteries to meet the load demand. The grid can supply power to conventional passive 12 V loads or intelligent loads capable of load shedding. There are no communication links between blocks and all functionality is accomplished via Bus voltage signalling.

A. PeCo grid legacy

The legacy system validated the autonomous control architecture and concept of the Peco grid. However, the system lacked practical implementation due to the high cost of the PLC and low power capability of the DC-DC converter utilized

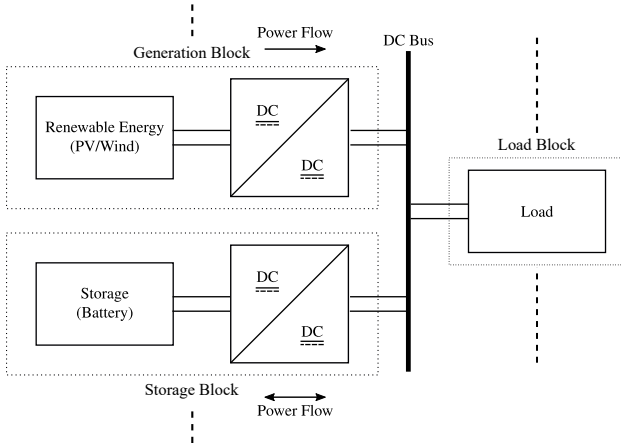


Fig. 2. Basic model of the PeCo grid

for prototype blocks. Key findings from the legacy system was that the PeCo grid has an ad-hoc architecture and the grid may be scaled by adding or removing blocks in a plug-and-play manner. Blocks on the grid autonomously configure themselves and co-ordinate their control during scaling which highlights the ease of use, scalability and personalization of the system for the end user whose only task is to connect blocks together.

B. Block control Protocol

The PeCo grid utilizes an innovative de-centralized control architecture and a bus voltage signalling based control algorithm is deployed at each block. The control algorithm was inspired by the concept of stigmergy and forms the crux of the technology. Stigmergy describes a mechanism of self-organising behaviour and coordination exhibited by social insects. The idea is that work performed by an agent modifies the environment which then stimulates a response from the same or other agents in the environment with the aim of returning the environment to homeostasis. This notion explains how colonies composed of simple insects with minimal intelligence collaboratively perform complex tasks without any apparent communication.

Relating stigmergy to the PeCo grid, blocks are considered to be agents with seemingly minimal intelligence and the environmental factor modified by them is the grid voltage. Any modification to the grid voltage by a block stimulates a response from that block and other blocks on the grid with the aim of returning the grid voltage back to a set nominal value. To achieve this, blocks have multiple modes of operation. Blocks infer the status of the grid from the grid voltage and select a mode of operation based on the status of the grid, see Fig. 3. To allow the grid voltage to be an information carrier, the V_{max} and V_{min} bounds of the grid are relaxed. Thus, the grid does not have a tight voltage regulation around the nominal grid voltage V_{nom} . Solar generation blocks have two modes of operation: MPPT mode and production curtail mode. In the MPPT mode of operation the generation block tracks

	Solar	Storage	Loads
V_{max}	Shutdown	Shutdown	No action
V_{nom}	Production curtail	Store energy	Deploy loads
V_{min}	MPPT	Grid support	Shed loads
	Shutdown /Restart	Shutdown /Restart	No action

Fig. 3. Grid voltage protocol used by the smart devices to select modes of operation

the maximum power point of the solar panel to ensure that all available solar energy is supplied to the grid. ES blocks have a grid support mode and storage mode. In the storage mode the block stores energy by charging the battery when there is a surplus production and discharges the stored energy when it is supporting the grid. Generation and ES blocks have a shut-down and a restart mode. The shut down mode protects against over and under voltage fault conditions. In this mode, a block enters a sleep mode to protect the elements on the grid. The restart mode is entered for grid black-start or when a block is recovering from a shut-down caused by a fault condition. Shut-down/restart modes operate within the same voltage band. However, they cannot co-exist on the same device and sequentially toggle between each mode. Toggling between shut-down and restart occurs until the system comes out of the fault condition and the block restarts without any user intervention.

The stigmergic approach to grid control allows for the global system to operate autonomously in a modular fashion without the need for blocks to communicate between each other. This means blocks can be added or removed from the grid at will and will begin to observe the environmental factor i.e. the grid voltage and work towards bringing about a stable grid. Further, this is how the PeCo grid technology is able to achieve ease of use and more importantly scalability.

C. Block communication

To convey grid status to users, pictures of facial expressions will be used. A back lit sad face will depict an unstable grid and a happy face a stable grid. With regard to individual blocks, a picture of an empty battery back lit by an led can communicate the battery is flat and the ES block needs charging. Once field trials are conducted it can be ascertained what and how further information needs to be conveyed to users.

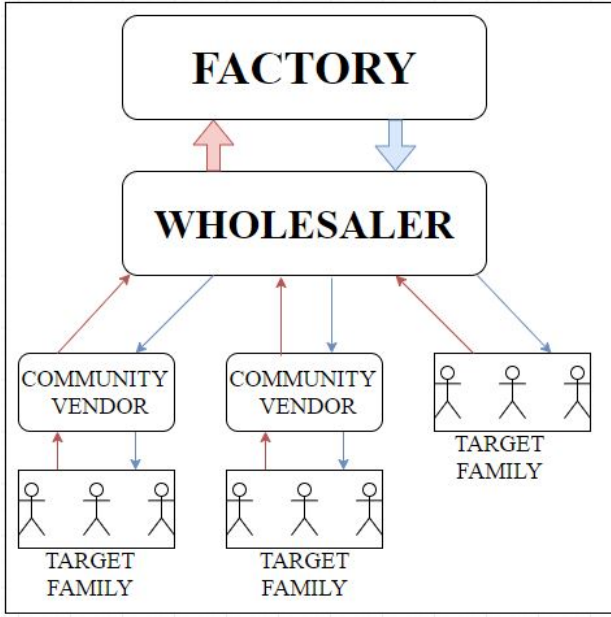


Fig. 4. Basic model of the PeCo grid

V. SYSTEM DEPLOYMENT AND DISTRIBUTION

A key attribute of distributed grids is rapid deployment. The PeCo grid can be sold in a modular fashion, where end users can purchase any of the blocks separately or kits consisting of several blocks bundled together. Blocks will be manufactured at factory and distributed to wholesalers within target regions such as large chain stores, supermarkets or hardware stores, see Fig. 4. Vendors within target regions can purchase blocks or kits from a wholesaler and re-sell them within target communities to target families. Target families may also cut-out the community vendor and purchase blocks directly from a wholesaler. Target families can purchase blocks just as they would a loaf of bread and the product becomes theirs.

A. Hub distribution

An alternative model to encourage entrepreneurship is a hub distribution within the community. Community vendors can purchase multiple blocks on hire purchase from wholesalers to set-up a PeCo hub. This hub will be within the community, amongst households and not as far away as wholesalers are. This hub targets families that cannot afford a kit or individual blocks. These families can rent ES blocks from a hub within the community. The vendor will have access to a hoard of generation blocks and will charge ES blocks and rent them out. Once discharged, the target family returns the ES block to the hub where it will be re-charged and rented out again. Whilst in possession of a rented ES block, the target family can improve their livelihood and earning potential so that they can eventually afford a kit or block of their own. Target families that do own ES blocks can also pay vendors to charge their blocks at the hub until they can afford a generation block of

their own. Once field trials have been conducted, it can be ascertained how this model will function in the real world and whether or not it is viable.

B. Product returns

In the event of there being a faulty block, target families can return and exchange the product directly to the wholesaler or to the community vendor, as depicted in Fig. 4 by the arrows. Target families do not have to have any technical knowledge and are expected to simply return faulty blocks to be exchanged for a new one.

The proposed idea is that once field trials have been conducted, the possible faults that the PeCo grid will encounter will be established. Faults can be categorised as being major or minor, for example a minor fault may be a broken cable or connector caused by user negligence whereas a major fault could be a manufacturing fault. Ideally, the hub can employ a community member as a hub technician who can be educated to handle any minor faults encountered. If it is established that the users negligence has caused the fault, they will be expected to pay the hub technician to repair. Hub technicians may be educated by literature in their language that is distributed by wholesalers. The reasoning behind this is that communities may be remote from wholesalers and it would be prudent to resolve minor faults on-site in the shortest possible time to prevent the target family from suffering any negative impact on their livelihood and earning potential. This also adds educational value to the community and creates jobs. Any major fault that the hub cannot resolve will be sent to the wholesaler or factory to be handled. It is imperative that faulty blocks be repaired or exchanged for a working block immediately on return or as soon as possible so that there is little to no negative impact on the target family livelihood and earning potential. Further, the target family is not expected to repair any faults encountered.

C. Product range

An introduction level kit or Type I kit will consist of one 30 W panel generation block and one 7Ah ES block. This system has a low capital investment but does not give the end user the lowest Wh/\$ and is meant only to meet basic low-energy use family needs prioritizing lighting and cell phone charging. A Type II kit consists of a 100 W panel generation block and one 60Ah ES block and a Type III kit consists of a 220 W panel generation block and one 100Ah ES block. Load capabilities of a Type II or Type III kit include television, refrigeration and heating and aim to meet high-energy use family needs. The blocks comprising kits may also be sold individually to allow users to scale and personalize their grid however they feel. Since the system is plug-and-play and autonomous, there is no need for a technician for installation and set-up or for the user to have knowledge of grids and electricity. Technicians are only required in the event of their being a faulty product that needs to be repaired. All users need to do is plug blocks together and the system will initialize and automatically configure itself. Type I kits and

TABLE I
PEAK POWER, STORAGE CAPABILITIES AND COST OF PeCo GRID BLOCKS

Level	Generation		Storage		
Type I	30 W	\$30	50 W	7 Ah	\$50
Type II	100 W	\$100	150 W	60 Ah	\$150
Type III	220 W	\$220	300 W	100 Ah	\$300

blocks are aimed at families that can afford a low capital investment whereas Type II and Type III kits and blocks are aimed at families capable of a larger capital investment. For the peak power, storage capabilities and estimated cost of kits and blocks, see Table 1. The products all operate on the same platform and can interact with each other. This implies that the entry level and high level products operate on the same grid and end users are not limited to using only one family but can seamlessly integrate higher level units as their financial situation improves.

VI. SYSTEM SCALING

The PeCo grid uses a three port connection idea, see Fig. 5. Each block has three connector ports which is the only access the end user has to the product. Blocks are simply interconnected at the ports to build the PeCo grid and the grid is scaled by plugging or un-plugging blocks from each other using a DC cigarette connector. The total peak power of a PeCo grid is determined from (1). This suggests the power capabilities of the PeCo grid can be scaled to meet any power demands.

$$Total(pp) = \sum RESblocks(pp) + \sum ESblocks(pp) \quad (1)$$

VII. ENHANCING THE TARGET COMMUNITY

The proposed community hub PeCo grid can be utilized for more than just retail and distribution of blocks. It is suggested that the hub may be utilized for educational purposes during the day. For example, the power generated can be used to run a school. At night, the hub may be used for community

entertainment by means of television and community members can come together. High power appliances such as refrigerators can be installed at the hub and used by the community to store medication and target families can pay the hub to store groceries. Target families can also scale their PeCo grid up to a point where they too can provide hub-like services to fellow community members. Eventually all target families can be scaled up to a hub and community members can assist each other with their PeCo grids.

VIII. MARKET VIABILITY

The proposed product range was based on estimate costs drawn from current prototype blocks as a bench mark. Work done is aimed at increasing market viability by reducing product cost whilst still maintaining product integrity. For example, lead acid is the current choice of battery chemistry for ES blocks due to it being the cheapest of all chemistries and being widely available. Product size is being reduced and optimised by operating DC-DC converters at higher frequencies. Reduction in physical size and weight of blocks will reduce shipping and packaging cost. Once block technology is optimised for cost, a comprehensive costing model can be established. The model will focus on making the PeCo grid affordable for people at the base of the economic pyramid i.e. those living on \$2 per day.

IX. CONCLUSION

The PeCo grid was proposed as a possible solution to address the energy poverty crisis in rural regions. The distributed generation model and de-centralized control architecture of the PeCo grid draws on the technology of existing smart grids. This methodology allows for rapid deployment of the system, ease of use and for the system to be scaled in a plug-and-play manner. The proposed product range to be distributed is able to meet the required Tier 1 low energy use family electricity demands and further proposed products as well as the scalability of the system allows for the Tier 2 high energy use family demands to be met.

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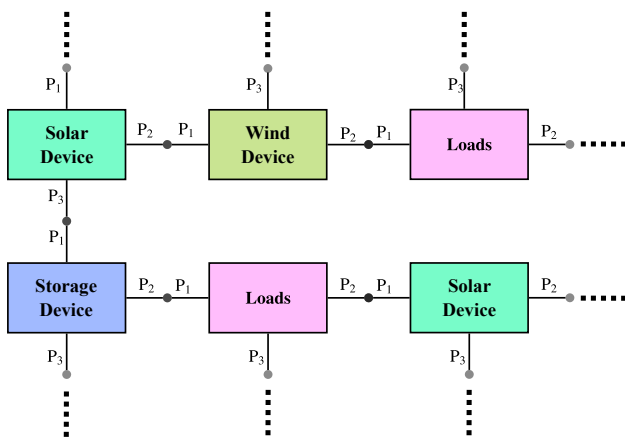


Fig. 5. Three port scalability

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