

An Autonomous Smart Battery for an Isolated 12 V Distributed DC Grid

Student Name: Muhammed Aswat

Student Number: 560468

A dissertation submitted to the Faculty of Engineering and the Built Environment,
University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for
the degree of Master of Science in Engineering.

Johannesburg, October 2018

Declaration

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

Signed this ____ day of _____ 20__

Student Name: Muhammed Aswat

Student Number: 560468

Abstract

An autonomous smart battery is developed to incorporate storage on an isolated 12 V DC grid called the PeCo grid. The PeCo grid is a personal consumer grid aimed at electrification of rural areas with no existing electrical infrastructure. In order to develop the smart battery a 12 V lead-acid battery is combined with a Dual Active Bridge (DAB) bi-directional DC-DC converter. Using this combination with the relevant control algorithms the smart device achieves grid stabilisation, black starting and fault protection without the use of a dedicated communication network. These features are achieved through the usage of a decentralised control architecture that is solely based upon the grid voltage. The smart battery is able to seamlessly integrate into an existing system due to its plug and play nature. A working prototype of the smart battery is developed and experimentally validated on the distributed energy system.

Acknowledgements

After months of writing this document, its conclusion has finally arrived. For this, I would like to thank Professor Willie Cronje for his continued guidance and advice throughout this research project and Prof Ivan Hofsajer for the discussions and lessons on power electronics. This work would not be possible had it not been for the technical staff at Genmin laboratories who aided me no matter the hour. It is also with great pleasure that I thank my parents for their continued support through this journey of life no matter what path I choose. Lastly, I can not stress how grateful I am for my friends and family who assisted in proofreading this document.

Contents

Declaration	i
Abstract	ii
Acknowledgements	iii
Contents	iv
List of Figures	x
List of Tables	xvii
1 Introduction	1
1.1 Research Outcomes	2
1.2 Chapter Overview	3
2 Distributed Energy Systems	5
2.1 Distributed Power Systems	5
2.1.1 Topologies	5
2.1.2 Control Strategies	6
2.2 DC-DC Converters	9

2.3	Storage on Grids	11
2.4	Conclusion	12
3	PeCo grid	14
3.1	Devices on the PeCo grid	15
3.1.1	Load Elements	15
3.1.2	Smart Generation	15
3.1.3	Smart Storage	16
3.1.4	Aggregated Grid Model	16
3.2	Grid Voltage Protocol	17
3.3	System Scaling	20
3.4	Conclusion	20
4	Lead-Acid Battery	22
4.1	Battery Models	22
4.1.1	Simple Battery Model	22
4.1.2	Thevenin Battery Model	23
4.1.3	Dynamic Models	23
4.2	Lead-Acid Operational Considerations	26
4.3	Conclusion	26
5	Dual Active Bridge	28
5.1	Lossless Dual Active Bridge	30
5.2	Lossy Dual Active Bridge	32

5.3	Selection of L_s	37
5.4	Conclusion	38
6	Control Algorithm	41
6.1	PeCo Grid Scenarios	42
6.1.1	No Generation on the Grid	42
6.1.2	Lightly Loaded Grid	42
6.1.3	Operational Grid	43
6.2	Battery Functionality	43
6.2.1	Soft Starting	43
6.2.2	Fault Detection and Protection	43
6.2.3	System Scaling	43
6.2.4	Battery Management	44
6.3	Voltage Inference Engine	44
6.4	Smart Battery as a Finite State Machine	45
6.4.1	Increase Supplied Power	47
6.4.2	Decrease Support	47
6.4.3	Increase Storage	48
6.4.4	Decrease Storage	48
6.4.5	Maintain Support and Storage	49
6.4.6	Transient Absorption	49
6.4.7	Shut-down	49
6.4.8	Restart	50

6.5	Battery Management	50
6.6	Output Capacitance	53
6.7	Conclusion	54
7	Smart Battery Performance	55
7.1	No Generation on the Grid	55
7.2	Lightly Loaded Grid	58
7.3	Fully Functional Grid	61
7.4	Scaling	64
7.5	Short circuit protection	65
7.6	Battery Charging	68
7.7	Conclusion	70
8	Conclusion	72
8.1	Future Work and Outlook	74
	References	75
A	Dual Active Bridge Magnetic Component Design	88
A.1	Introduction	88
A.2	Leakage inductor design	88
A.3	High frequency transformer design	90
A.4	Conclusion	91
B	Spice Simulation	92

B.1	Introduction	92
B.2	Conclusion	92
C	Dual Active Bridge Prototype	94
C.1	Introduction	94
D	Thermography of the Dual Active Bridge	102
D.1	Introduction	102
D.2	Conclusion	104
E	Designing a Filter Network for High Current DC-DC Converters on a Low Voltage DC Grid (SAUPEC 2018 Paper)	105
	Abstract	106
E.1	Introduction	106
E.2	Background	107
E.3	Bulk capacitance	109
E.4	Transient Voltage Suppression	110
E.5	Pi Filter	112
E.6	PCB Layout Considerations	114
E.7	Filter Performance	114
E.8	Conclusion	116
	References	117
F	Implementation of Control Algorithm	119

G	PeCo Grid Test Bed	120
G.1	Introduction	120
G.2	Centre bus and scalability	121
G.3	Devices on PeCo gird	122
G.4	Digital Load	122
G.5	Conclusion	123
H	Battery Testing	124
H.1	Introduction	124
H.2	Battery Loading	124
H.3	Open Circuit voltage and SOC relationship	125
H.4	Conclusion	125

List of Figures

1.1	Difference between central and distributed electrical power networks.	3
3.1	Block diagram showing smart devices on the PeCo grid.	15
3.2	Model of load elements on the PeCo Grid.	15
3.3	Model for sources and storage devices on the PeCo grid.	16
3.4	A possible version of the PeCo grid containing multiple sources, storage and load elements.	18
3.5	An aggregated model of the PeCo grid shown in Figure 3.4 reduced to a Thevenin equivalent where the smart battery connects at V_{gr} . .	18
3.6	Grid voltage protocol used by the smart devices to select modes of operation.	19
3.7	Operational region of storage and generation devices on the PeCo grid.	21
3.8	Scalability of the PeCo grid using a three port configuration.	21
4.1	Simple battery models.	23
4.2	Nonlinear Thevenin equivalent model of a lead-acid battery.	24
4.3	Lead-acid battery discharge characteristic of a 7 Ah battery obtained experimentally as described in Appendix H where the battery is discharged under constant current and the load is disconnected at 190 min.	24

4.4	Open circuit voltage vs SOC of a 7 Ah lead acid battery obtained experimentally as described in Appendix H where the battery is discharged under a constant current of 1 A and the SOC is computed using Coulomb counting.	25
5.1	Dual active bridge DC-DC converter topology.	28
5.2	Lossless model of the DAB.	29
5.3	Operational waveforms for the DAB using phase shift modulation where T_1 and T_2 are the periods of the square waves and $T_1 = T_2$. . .	29
5.4	Inductor current and voltage waveforms for phase shift modulation over one switching period T_S	30
5.5	Power transfer to V_{gr} when varying α as per equation (5.12) for $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ and $V_{gr} = 12 \text{ V}$	32
5.6	Measured power transfer on the experimental prototype to V_{gr} when varying α for $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ and $V_{gr} = 12 \text{ V}$	33
5.7	Lossy DAB model where R is the lumped coil resistance.	33
5.8	Simulated inductor current when the series losses are varied.	34
5.9	Core loss model for the DAB.	35
5.10	Experimentally measured and estimated power loss using equation (5.18) for $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ and $V_{gr} = 12 \text{ V}$	36
5.11	Ideal inductor current and delay α for $P = 150 \text{ W}$ when $V_1 = 12 \text{ V}$ & $V_{gr} = 12 \text{ V}$	38
5.12	Ideal inductor current and delay α for $P = 150 \text{ W}$ when $V_1 = 14 \text{ V}$ & $V_{gr} = 12 \text{ V}$	39
5.13	Ideal inductor current and delay α for $P = 150 \text{ W}$ when $V_1 = 10 \text{ V}$ & $V_{gr} = 12 \text{ V}$	39
5.14	Measured DAB power transfer of built experimental prototype when $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ & $V_{gr} = 12 \text{ V}$ when loaded with a varying resistor.	40

5.15	Measured efficiency of the experimental prototype for $L_s = 1.8 \mu\text{H}$ when $V_1 = 12 \text{ V}$ & $V_{gr} = 12 \text{ V}$	40
6.1	Block diagram of the smart battery showing key components and their interactions.	41
6.2	Grid model of the PeCo grid used to test the smart battery which connects to V_{gr}	42
6.3	Grid voltage levels utilised for grid inference engine in Table 6.1. . .	45
6.4	Smart battery instruction cycle routine.	46
6.5	Grid support state machine for the smart battery.	46
6.6	Battery charge state machine for the smart battery.	47
6.7	ΔP for increase and decrease support/storage states	48
6.8	Transient absorption logic.	50
6.9	Start up procedure for the smart battery on a PeCo grid.	51
6.10	SOC computation and reset procedure used for battery management. .	52
6.11	Lead-acid battery charge curve.	53
6.12	Model of smart battery when changing ΔP	53
7.1	Test set-up used for the varying load with no generation where $R_{trx} = 8 \text{ m}\Omega$ and $2.5 \Omega \leq R_L \leq 17.5 \Omega$	55
7.2	Variable resistor profile used for the varying load test.	56
7.3	Voltage and current response when varying the load with no generation. .	56
7.4	Test set-up used for the step load experiment where $R_{trx} = 96 \text{ m}\Omega$ and $R_L = 0.96 \Omega$	57
7.5	Grid voltage and load current when disconnecting a 0.96Ω load. . .	57
7.6	Grid voltage and load current when connecting a 0.96Ω load	58

7.7	Test set-up when varying generation with no loading where $R_{trx} = 64\text{ m}\Omega$	58
7.8	V-I curve for generation emulator implemented using a current limited DC bench supply.	59
7.9	Varying generation profile.	59
7.10	Performance curves when varying generation with no passive loading.	60
7.11	Test set-up for step response when connecting a generation element with no passive loads on the grid. $R_{trx} = 64\text{ m}\Omega$	60
7.12	Smart battery response when connecting a generation device.	60
7.13	Smart battery response when disconnecting a generation device.	61
7.14	Test set-up for a fully functional grid with variable generation and load where $R_{trx1} = R_{trx2} = 48\text{ m}\Omega$	61
7.15	Smart battery response when varying generation for a $4.5\text{ }\Omega$ fixed load for the in Figure 7.14.	62
7.16	Smart battery response when varying both the generation and load using the set-up in Figure 7.14.	63
7.17	Test set-up used for scalability test where $R_{trx1} = 16\text{ m}\Omega$, $R_{trx2} = 32\text{ m}\Omega$, $R_{trx3} = 96\text{ m}\Omega$, $R_1 = 0.83\text{ }\Omega$ and $R_2 = 0.95\text{ }\Omega$	64
7.18	Performance waveforms of the two batteries when scaling system from 150 W to approximatly 300 W.	65
7.19	Performance when a 300 W device is connected.	66
7.20	Failed restart where one device is trying to start up a 300 W load.	66
7.21	Grid start up when a second smart battery is inserted.	67
7.22	Test set-up used for fault event test when a short circuit event occurs where $R_{trx1} = 16\text{ m}\Omega$, $R_{trx2} = 32\text{ m}\Omega$, $R_{trx3} = 0.96\text{ m}\Omega$ and $R_1 = 0.45\text{ }\Omega$	67

7.23	System behaviour during a short circuit fault.	68
7.24	Zoomed in view of t_0 when the short circuit fault event occurs. . . .	69
7.25	Restart attempt at t_1 during the short circuit fault event.	69
7.26	Successful restart after short circuit event has cleared at t_2	70
7.27	Battery end of charge waveforms with no loading and only generation present.	70
A.1	Image of the constructed inductor	90
A.2	Photo of the built planar transformer.	91
B.1	LT Spice simulation used to test and develop a DAB converter. . . .	93
C.1	Prototype DAB DC-DC converter.	94
C.2	Overview of the DAB converter	95
C.3	Overview of the H-Bridge Driving circuit.	96
C.4	High side driver and DC bus capacitors for the half bridge circuit. .	97
C.5	Bridge protection circuit for one half bridge.	98
C.6	Isolated analogue feed-back diagram.	99
C.7	MCU circuit diagram.	100
C.8	Power supply circuit diagram for supply integrated circuits.	101
D.1	Test set-up used to thermally map the DAB.	102
D.2	Thermal snapshot at the beginning of recording.	103
D.3	Snapshot of thermal recording at 43 s.	103
D.4	Steady state temperature of the DAB after 8 minutes.	104

E.1	Block diagram representation showing the key components on the LVLP Picogrid where i_1 & i_2 are the DC-DC converter current flow directions.	108
E.2	Core components for an arbitrary DC-DC converter where the filter network is a low-pass filter.	108
E.3	Basic circuit elements for a DAB.	108
E.4	Simplified RC model used to size the bulk capacitor where V_G is the nominal grid voltage and i_1 is the maximum current the converter can source.	109
E.5	Expected and simulated ripple voltage of the DAB shown in Figure E.3 using simplified RC approach to estimate required bulk capacitance under constant power draw while increasing the output capacitance at a constant 50 kHz switching frequency with grid parameters as per Table E.1.	110
E.6	Measured bus voltage when drawing 30 W from the DAB converter using a resistor	111
E.7	Method for idealising a non-ideal capacitor using capacitor paralleling to form a bank (C_B').	111
E.8	Simulated effects of the addition of the snubber showing the damping of the higher order frequencies on the bus	113
E.9	Addition of LC filter to form a pi network.	113
E.10	Layout of the PCB where l_1, l_2, l_3, l_4 are the PCB track lengths between component terminals.	114
E.11	Practical model for LVLP DC Grid.	115
E.12	Measured bus voltage using the recommended filter network at a power transfer of 89 W.	115
G.1	Diagrammatic representation of the test bed.	120
G.2	Image of the constructed PeCo grid.	121

G.3	Centre bus of the PeCo grid.	121
G.4	Smart battery devices on the PeCo grid.	122
G.5	Loads on the PeCo grid: 300 W resistive load, computer monitor utilising a 12 V off the shelf inverter, cellphone charger and three lights.	123
G.6	Circuit diagram for the digital load.	123
H.1	Test set-up used to test the lead acid battery.	124
H.2	Lead Acid battery discharge characteristic obtained discharging a 7 Ah RITAR RT1270 at a constant current of 1 A.	125
H.3	Battery terminal voltage of RITAR RT1270 under constant current discharge of 1 A.	126

List of Tables

1.1	Summary of energy Tier levels as defined by the World Bank in [1]	2
5.1	DAB Specifications for the PeCo Grid	37
6.1	Grid voltage inference engine	45
6.2	Lead-acid battery terminal voltage inference engine where V_{bat} is the terminal voltage	45
A.1	Specifications of the designed leakage inductor L_s	90
A.2	Specifications of the designed high-frequency transformer	91
E.1	Grid Parameters	115
E.2	Properties of the capacitor bank and LC filter	115

Chapter 1

Introduction

This dissertation focuses on the development of a smart battery to add storage to a 12 V solar powered standalone grid capable of electrifying rural dwellings. Africa remains one of the least electrified continents in the world with most regions having no existing medium voltage or high voltage electrical transmission lines. In order to electrify these primarily rural areas, it is necessary to adopt innovative rural electrification methods.

The most common electrical power systems currently in use are based on a predominantly central generation strategy depicted in Figure 1.1a. In central generation, a large electrical power station generates the electricity required by loads which are mostly situated further away from the power station [2]. In order to transfer electrical power to the required loads, a transmission line network is employed [2].

Large-scale power stations generate electricity via coal, nuclear or hydro energy [3]. The primary advantage of these power stations is their high power capability. However, the drawbacks of power stations are the large capital contribution and long construction periods required to commission new plants [4]. This makes it unlikely that power stations will succeed in addressing the electrification crisis in Africa.

Additional disadvantages of fossil-fuelled power stations include adverse environmental effects and the limited quantities of fossil fuel availability. The depletion of fossil fuels has resulted in a constant rise in the cost of fossil fuel based energy. Solar energy, in contrast, has been undergoing a price reduction due to its increased popularity [4]. The continued cost reduction of solar-based power systems makes a strong argument for new electrical power systems to be based on renewable energy sources.

In order to ensure the success of a new electrification method, it is important to

identify the electricity requirements in rural environments. Reference [1] identifies the main uses of electricity by rural communities as:

- Lighting
- Cellular phone charging
- Television
- Refrigeration
- Heating and Cooking

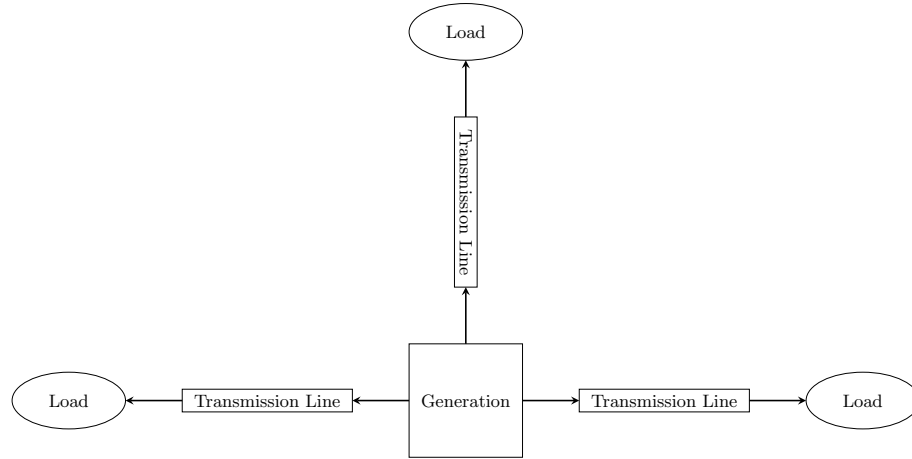
Lighting is the highest priority for people in rural areas followed by cellular phone charging which forms a tier one energy system as shown in Table 1.1. Standalone DC smart grids based on renewable energy is an innovative solution that could potentially address the electrification crisis in Africa. DC Smart grids are able to meet the above listed requirements. These systems are scalable, require minimal start-up capital, can be rapidly deployed and use renewable energy sources.

Task	Tier 1	Tier 2	Tier 3
Lighting			
Cellular Phone Charging			
Television			
Refrigeration			

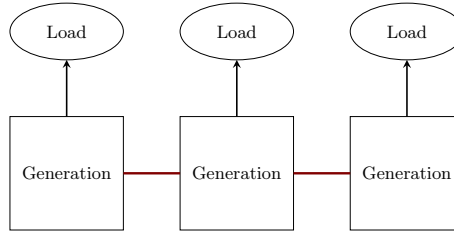
Table 1.1: Summary of energy Tier levels as defined by the World Bank in [1]

1.1 Research Outcomes

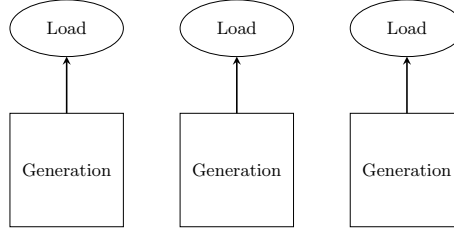
- Presenting a potential solution that can be used to help resolve the energy crisis currently being experienced in Africa.
- Identifying functional requirements for a smart battery
- Algorithms allowing energy storage on a distributed DC grid
- Practical realisation of a plug and play smart battery capable of interfacing to an *ad hoc* 12 V DC grid.



(a) Simplified representation of a central generation scheme.



(b) Possible representation of a generation scheme that is distributed and interconnected.



(c) Possible representation of a generation scheme that is distributed and islanded.

Figure 1.1: Difference between central and distributed electrical power networks.

- Investigating and identifying design considerations when designing a dual active bridge for low-voltage DC grid systems.
- An inference engine for a distributed DC grid that allows for information transfer without the use of a dedicated communication network.

1.2 Chapter Overview

- **Chapter 2** reviews current research trends in distributed energy systems which contextualises the presented work. Topological variations and control algorithms being developed currently are reviewed. A survey of DC-DC converters and storage options being developed for DC grids is conducted.

- **Chapter 3** defines the environment in which the smart battery will operate. A distributed power system called the PeCo grid is introduced and its potential to solve the electricity crisis is highlighted. In this chapter, the required model for the smart battery is defined and the communications protocol for this system is established.
- **Chapter 4** discusses common models for a lead-acid battery. This battery technology is the selected passive storage element for the smart device.
- The necessary considerations of a dual active bridge DC-DC converter to act as an interface between the lead-acid battery and the PeCo grid is discussed in **Chapter 5**. The voltage-based loss estimator that is presented, aides in the management of the lead-acid battery.
- The algorithms developed in **Chapter 6** transform the non linear passive model discussed in **Chapter 4** to the equivalent model defined in **Chapter 3**. The algorithms are implemented on the DC-DC converter that is discussed in **Chapter 5** and allows the smart battery to achieve the required grid functionality.
- The performance of the smart battery is evaluated in **Chapter 7**. Testing is conducted to validate the algorithms and the results are captured in this chapter. **Chapter 8** summarises and draws conclusions from the conducted research.

Chapter 2

Distributed Energy Systems

The distributed generation schemes depicted in Figures 1.1b & 1.1c shows that generation is done at the point of consumption. Distributed energy systems can be wind based as in [5, 6] or solar based as in [7, 8]. Hybrid systems developed in [9–13] use both forms of generation including hydro generation. A hybrid solution provides a more consistent generation profile as wind turbines can generate electricity at night or during overcast conditions.

Distributed power systems offer a multitude of advantages over a more centrally based scheme that utilises large power stations. One such advantage of a distributed system is the absence of a transmission network. This reduces the cost and construction time of newly commissioned systems. Renewable energy based solutions are environmentally friendly as they generate electricity from clean energy instead of fossil fuels. Fossil fuel based systems such as coal power stations cause carbon emissions that contribute to pollution and global warming [14, 15]. A key disadvantage of solar and wind energy is their inability to provide consistent yield due to their time-varying nature. This is overcome by adding storage, resulting in a stable power system [10, 16–20].

2.1 Distributed Power Systems

2.1.1 Topologies

Various topologies of distributed systems are prevalent such as the isolated grids in [16, 21, 22] or the non isolated grids as in [9, 10, 23]. An isolated grid is defined as one which has no connection to a traditional utility provider whilst non-isolated

systems have a connection to a utility grid. These grids are dependent on the utility grid to provide energy when the renewable sources are not able to meet the load demand. In comparison, isolated systems are required to ensure that the remote grid is fully sustainable throughout the operational period as there is no connection to the utility grid. Isolated systems are applicable to rural electrification where there is no existing electrical infrastructure. The isolated grids are based on either AC [24–27] or DC [10, 23, 28, 29].

When electricity generation by the renewable sources is low, these grids rely heavily on storage to ensure the operability of the remote grid. During a low generation period load shedding or optimisation strategies can be implemented to prolong or ensure the longevity of the grid [30–33]. When storage is completely depleted and the grid is required to be functional, redundant diesel generators can be used to supply electricity as a last resort [10, 11, 34].

Nanogrids and picogrids are topological variants of the standalone DC grid. These grids operate on a low voltage and have low power capabilities [7, 35–38]. The power capacity of these variants is lower than that of the more commonly known microgrids. Picogrids and nanogrids are aimed at single buildings or households. Nanogrids can meet all the requirements outlined in Chapter 1 except heating and cooking. This makes these grids a tier two or three power system based on the classification framework laid out in [1]. Cooking and heating can be done through non-electrical means such as gas.

A nanogrid system consists of a minimum of three fundamental building blocks: a generation block, a storage block and a load block. Cluster-based nanogrids [7, 8, 39] create a cluster of the three blocks. Each cluster located within a single building is interconnected to the neighbouring building which has a cluster. Similarly, multiple neighbouring clusters are connected to create a power-sharing network. This results in a more diverse power system in comparison to the single nanogrid. This diversity results in a highly stable network when operating under normal conditions.

2.1.2 Control Strategies

Distributed grids can use a centralised or de-centralised control architecture to regulate the grid [30, 40]. Centralised control uses a single intelligence to control all elements on the grid at a global level and requires a communication link between the elements and the controller unit. Distributed control has control actions distributed

amongst the various elements on the grid. Hybrid control uses both central and distributed control. The fast controller action is implemented locally and slower control actions are implemented globally.

A distributed control architecture can have a communication link between the various functional blocks. An autonomous control architecture is one where the control action is distributed but there is no communication link between the various elements. This architecture is illustrated in the autonomous grids presented in [10, 28, 29, 41]. In place of a dedicated communication link, bus voltage signalling is utilised as shown in [10, 42–44]. Bus voltage signalling is a method where the grid voltage is used to infer information regarding the state of the grid. The inferred information is used to implement the relevant actions. This makes the grid voltage the information carrier on these systems. These controllers operate on the principle of stigmergy where the objective of each element is locally achieved resulting in the achievement of a greater global objective [32, 45, 46].

A central control architecture offers improved current sharing elements on the grid. It is possible to achieve a tighter bus voltage regulation about the nominal grid voltage on a central architecture. Central controllers make it easier to implement coordinated strategies such as black starting and state of charge distribution of energy storage elements on the grid. The main disadvantage of this control is the computational burden is placed on a single entity which reduces robustness and performance as the system size increases [30, 40]. A hybrid control strategy that amalgamates both architectures offers the advantages of central and autonomous control. Hybrid controllers, however, do require a communication link.

Hierarchical control uses the principle of multi-level control where the primary controller is responsible for ensuring the overall stability of the grid [30, 40]. Secondary or tertiary control can be used to control individual aspects of the power systems. Primary controllers are responsible for ensuring power regulation on the bus while secondary and tertiary controllers can be used to manage specific aspects such as voltage regulation of the grid, MPPT of the solar functional block or battery management of the storage block. A disadvantage of traditional hierarchical control is the inability to effectively manage situations when multiple functional blocks attempt to achieve the same objective [40].

Various control strategies can be implemented using either of the architectures discussed above. A linear PID controller which is the simplest form of feedback control, presented in [47], is not well suited for the microgrid environment due to the

nonlinearities and time variance of the system. Basic PID controllers can be tuned for a specific grid set-up if the generation or load profile is constant. Distributed energy systems utilise solar or wind energy for generation which varies non linearly as a function of time. This makes linear controllers ineffective on the distributed grid. In order to overcome this it is possible to use cascaded PID control schemes in [48–50] where a PID controller is cascaded with a non-linear control strategy. Nonlinear controllers such as sliding mode control can be implemented to grid systems to achieve robust control [47].

A common strategy for autonomous grids is droop control [23, 41, 51, 52]. In droop control, the required controller action is determined by the bus voltage or frequency of the grid. This feature makes it possible to implement this strategy without a communication link. As well as regulation, weighted droop control uses parameters such as the State of Charge (SOC) of storage to ensure better SOC distribution amongst the grid [40, 53] without the use of a communication link. Droop coefficients can be adaptive as shown in [54] where the controller adapts for better regulation of the grid.

Another common strategy is the use of state machine concepts demonstrated in [9, 54–56]. Various modes of operations are defined as states. The boundaries of these states are discretely defined using different voltage ranges. Within each state, control action such as PID or alternative schemes can be implemented to achieve the desired mode of operation. Elements undergo state transitions dependent on the present value of the grid voltage and enter new states with specific modes of operation which are geared towards stabilising the grid.

A common issue that arises with state machine based definitions is the false switching between states when the bus voltage is near a boundary definition as described in [56]. Fuzzy control presented in [57, 58] can alleviate this problem. In place of discrete bounds of operation, a fuzzy boundary is used which helps to overcome the false switching between states experienced in state machine based approaches.

An optimal control strategy can be achieved on systems which have consistent profiles using machine learning methods discussed in [59, 60]. These controllers evolve and adapt over time in order to optimise the control action. With this approach the longer the controller is acting on the grid the more optimal its control action. This strategy fails when there is a high variance on the grid in terms of load or generation profiles.

Although various control strategies currently exist reference [61] identifies one of

the areas currently requiring attention on distributed energy systems is the control strategies for energy storage elements. Reference [40] evaluates 67 various control strategies published to establish the technology readiness level of distributed energy systems. This evaluation was performed using the standardised scoring index developed in [62, 63]. This index ascertains how ready a technology is for end-user deployment. None of the current strategies meet the required minimum rating of six in order for it to be classified as “ready for end-user deployment”. Energy storage on autonomous systems have the lowest scores and more research is required to improve its technology readiness level. This dissertation focuses on developing the control algorithms for interfacing storage to an autonomous DC grid. The algorithms developed for storage are used to form the smart battery which is a storage solution for DC grids. The smart battery in this study interfaces a lead acid battery to an autonomous 12 V distributed DC grid.

2.2 DC-DC Converters

DC-DC converters are the cornerstone devices that make DC grids a possibility. Converters which operate on DC grids are required to have bucking or boosting capabilities in order to step-down or step-up the voltage from generator or storage functional blocks. This can be accomplished using the simple buck-boost converter demonstrated [64, 65]. However, isolated topologies are preferred due to their inherent fault tolerance because of the galvanic isolation between the input and output ports. The simplest isolated DC-DC converter that performs both bucking and boosting is the flyback converter [10].

Uni-directional DC-DC converters are used for interfacing generation functional blocks to the grid as they only supply energy to the grid and have uni-directional current flow. Storage elements require converters with bi-directional capabilities to cater for charging and discharging of batteries. Bi-directional current flow can be achieved by anti paralleling two uni-directional converters as done in [10].

The Isolated Bi-directional Converter (IBC) is a single device that can allow two quadrant current flow (i.e current can leave or enter the converter). In the IBC family the simplest devices are ones which only use two switching elements such as the bi-directional fly-back, dual-Cuk and Zeta-Sepic converters [66–72]. Devices with only two switches typically have a lower power rating in comparison to topologies which use more than two switching devices. A common topology that uses more than two switching devices is the Dual Active Bridge (DAB) DC-DC converter [66, 67, 71].

The DAB converter is used in UPS supplies, smart grids and electric vehicle charging [66, 67, 71, 73, 74]. It is preferred over other topologies due to the high power capability and the isolation between the grid and battery bank. The eight switching devices of the DAB results in higher current capabilities due to the decrease in conduction loss. The switching of multiple switches results in a complex driving scheme in comparison to converters utilising fewer switches. An additional disadvantage of this topology is the inefficiencies during light loading or when there is a drift from the rated voltages. Efficiency at light loading can be improved by using the current fed DAB converter instead of the conventional voltage fed converter [75, 76].

Switching of the DAB is typically done by IGBTs or MOSFETs [67, 73, 77–79]. Soft switching can be implemented on the DAB resulting in greater reliability and a reduction in the likelihood of a switching device failing due to the decreased strain placed upon the switches.

Applications of the DAB can be found in both AC and DC grids [24–26, 73, 74]. For AC grids [24–26] the DC output of the DAB is inverted directly or by using additional inverters. Reference [24] presents an isolated $220\text{ V}_{\text{RMS}} - 220\text{ V}_{\text{RMS}}$ transformer while [26] operates on a 380 V isolation transformer. DAB based solid state transformers have an advantage over conventional 50 Hz AC transformers as the high-frequency link requires physically smaller magnetic components for the same power rating.

On a DC grid, the DAB can interface a battery bank to the grid by either stepping up or down the voltage of the battery bank. Reference [77] presents a 336 V DC bus to a 12 V battery bank capable of transferring 1 kW . The DAB presented in [77] is asymmetrical as the same power is not transferred in both directions. Reference [66, 77] highlights the challenges when designing converters capable of doing high currents on the 12 V port. Similarly, [80, 81] presents DABs which have a high voltage grid with a low voltage battery bank. However, the power flow is symmetrical in these cases. A 12 V to 24 V DAB capable of delivering 600 W is presented in [78] for applications on a smart grid. However, the validation and testing of this system was only done through resistive loading and only unidirectional capabilities were tested.

Different models of the DAB are presented in [66, 67, 73, 77, 82, 83] which can be used to design DAB converters. Reference [67, 73, 77] uses a lossless model while [66, 82] factors in losses. The small signal model developed by [83] indicates that when the DAB is operating in discontinuous conduction mode the voltage at the output begins to have low-frequency oscillations. This might be problematic in

autonomous low voltage systems.

It is not common for the DAB to be applied in very low voltage systems where the input and output voltages are matched. The more commonly found converter steps up a low voltage to a higher voltage. This work will focus on identifying the challenges and considerations when interfacing the DAB to a 12 V – 12 V system.

2.3 Storage on Grids

Storage of electrical energy for grid-based applications is achieved through gas, hydro or chemical methods [84–86]. Pumped air storage or pumped hydroelectric storage are methods of gas and hydro storage. These methods are more applicable to power systems greater than 100 MW [86]. They require specific geographical features such as salt caravans or large bodies of water on elevated terrains which limits the regions where they can be implemented. Chemical storage is done in the form of batteries. This form of energy storage is more applicable to a microgrid and its smaller variants.

The lead-acid battery is still the cheapest battery technology currently being applied to grid installations [85, 87]. Its low cost and the modular packaging make it a highly popular choice in grid installations. The drawback of this battery is the volume to energy ratio is larger than other technologies which results in larger battery installations. This does not factor heavily in grid installations as they do not usually require mobility or have space constraints. An additional disadvantage of lead-acid batteries is the low number of charge cycles before the battery reaches its end life. End life reduction occurs if the battery experiences regular overcharging or a high depth of discharge [86].

Two types of lead-acid batteries can be found: flooded and valve regulated. Flooded batteries require maintenance due to electrolytic depletion that occurs with usage while valve regulated batteries are maintenance free. Although the lead-acid battery is a highly mature technology [84, 86] it is still an active area for research. Current work looks at improving performance and increasing the longevity of the battery [84]. Research is also being conducted on battery health management systems [88–90] and charging algorithms [91–93]. Advanced battery models are being pursued due to the limitations of existing models as they do not adequately capture the state of charge and state of health [94–97].

Lithium-ion is an alternative to the lead acid battery [86, 98]. These batteries have a

higher energy density in comparison to lead acid which results in a smaller packaging for the same capacity battery. A correctly managed lithium-ion battery provides more charge cycles than a lead acid which results in a longer lifespan. Coupled with this, lithium-ion batteries are the most efficient of the batteries discussed in this section [99, 100]. The major drawback of this technology is the high cost and sensitivity to overcharging which may result in battery overheating. The sensitivity to overcharging can be overcome by using accurate chargers and algorithms as discussed in [101–103].

An alternative to the modular packaging of batteries is the sodium sulphur batteries [86, 104–107]. These batteries offer many advantages such as high depth of discharge (90% [107]), low cost, long life and minimal environmental impact. The major challenge that these batteries experience is the high operating temperatures of over 300 °C [86, 105]. A drawback of this technology is the highly reactive nature of sodium with air. This highly reactive nature results in safety concerns when using this technology.

Vanadium redox is a non-modular battery technology [86, 108–110]. This low-cost battery technology has garnered a lot of research in recent times due to its extremely long life of approximately 30 years discussed in [86]. This is substantially longer than any of the above-mentioned technologies. Although this technology possesses a long lifespan it has a very low energy density resulting in large battery installations. This battery is the least mature of all the technologies reviewed in this section.

An alternative to battery banks for storage is to use super capacitor banks [86, 100, 111–113]. Similar to lithium-ion, super capacitors possess high efficiencies [100]. The disadvantage of this technology is the high cost and low energy density of this storage. Super capacitor systems are usually proposed in conjunction with storage technologies that are capable of storing more energy [111, 112].

2.4 Conclusion

Distributed energy systems allow for renewable-based scalable electrical power systems. Due to the unpredictability and lack of production certainty from renewable generation, storage is required on these systems. Storage can be implemented using chemical methods such as batteries. The control algorithms required for storage on distributed DC grids needs more research as the currently proposed strategies are not mature and are not ready for commercial implementation. These strategies

do not adequately deal with the time variance and nonlinearity of an autonomous distributed DC power system. Isolated bi-directional converters are required for interfacing batteries to DC grids. The DAB converter is bi-directional in nature and is attractive due to its high power capabilities over other topologies. From the current technologies being used in grid installations, the lead-acid battery remains a popular choice due to its low cost, modularity and high maturity. This battery requires battery management techniques to ensure the longevity of the battery. This chapter has reviewed current research trends in distributed energy systems and established storage solutions as an area that requires research attention. Chapter 3 develops the distributed environment in which the smart battery storage solution will operate.

Chapter 3

PeCo grid

The Personal Consumer (PeCo) grid is a 12 V distributed energy system aimed at single households with particular attention to the electrification of rural Africa. A 12 V system is able to leverage the abundance of currently manufactured household appliances that have been developed for camping and recreational vehicles. These appliances are built to operate on a 12 V lead acid battery for use in off-grid locations.

A diagrammatic representation of the of the PeCo grid is shown in Figure 3.1. Electricity generation is accomplished through the use of solar panels and wind turbines. When there is surplus energy from generation, batteries store this energy. Smart batteries also provide support to the grid when the generation devices are not able to meet the load demand of the grid. Loads on the grid can be passive 12 V loads or have intelligence that allows for the implementation of load shedding strategies. Figure 3.1 shows that the interaction between the three devices is accomplished without the use of a dedicated communication link. The lack of a dedicated communication link and the absence of a connection to an electrical utility results in the PeCo grid being classified as an autonomous grid.

In order to commission a new grid or install a smart device into an existing grid, the end user is simply required to plug a two wire connector into a socket. The smart devices on the grid automatically reconfigure themselves when this event occurs and no further user intervention is required.

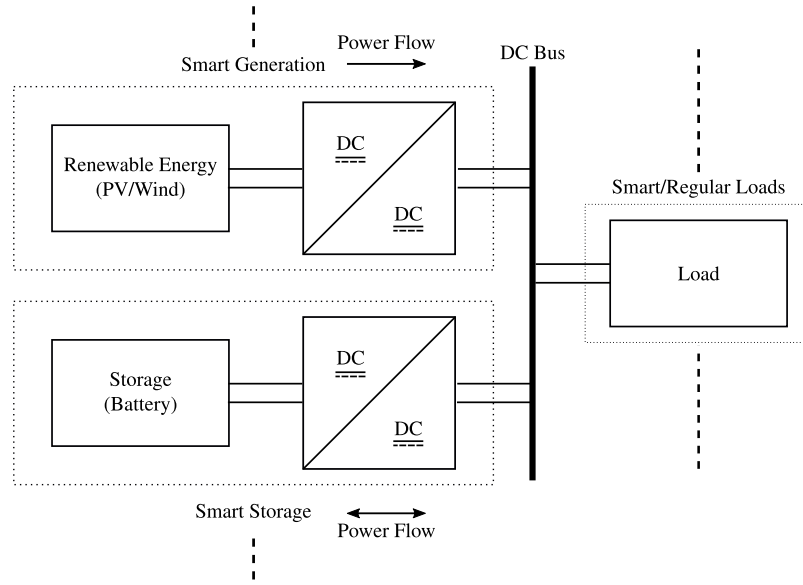


Figure 3.1: Block diagram showing smart devices on the PeCo grid.

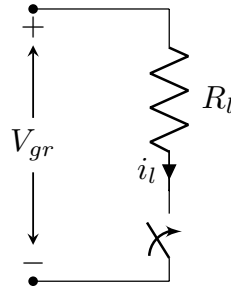


Figure 3.2: Model of load elements on the PeCo Grid.

3.1 Devices on the PeCo grid

3.1.1 Load Elements

Loads are the simplest elements on the PeCo grid and are modelled in Figure 3.2. The load is simply reduced to a switched resistor as the capacitive and inductive elements of the load tend to open-circuits and short-circuits respectively during steady state DC conditions. The switch in Figure 3.2 can be active to capture the behaviour of smart loads or passive for conventional loads.

3.1.2 Smart Generation

Smart solar/wind devices consist of a single solar panel or wind turbine connected to a uni-directional converter as illustrated in Figure 3.1. A single solar panel or wind

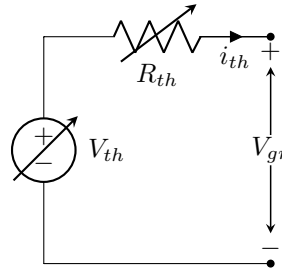


Figure 3.3: Model for sources and storage devices on the PeCo grid.

turbine topology is preferred over a string topology. This allows maximum power to be extracted from each element as the weakest element does not determine the maximum power output as in a string topology. The output power of these devices is controlled by manipulating the duty cycle of the switch mode converter. The behaviour when modulating the average output power is modelled using the circuit shown in Figure 3.3. In this model, the generation device is a variable Thevenin voltage and resistor. As current flow is only uni-directional for generation devices it implies that $V_{th} \geq V_{gr}$. This constraint ensures that i_{th} only leaves the device resulting in electrical power being transferred to the grid.

3.1.3 Smart Storage

A smart battery comprises of a battery connected to a bi-directional DC-DC converter. This combination is able to store and supply energy in order to stabilise the grid. The output voltage of the converter is always positive but the current i_{th} can leave the device for grid support or enter for battery charging. This behaviour is captured using the model in Figure 3.3. During storage mode $V_{gr} > V_{th}$ which ensures that the current flow is $-i_{th}$ resulting in energy storage. During grid support mode the storage element exhibits the same characteristic as a generation element where $V_{th} \geq V_{gr}$ and the current flow is i_{th} . The positive current flow results in the battery supporting the grid. The equivalent V_{th} and R_{th} values are controlled by the modulation scheme and control algorithms driving the converter.

3.1.4 Aggregated Grid Model

A potential version of the PeCo grid is shown in Figure 3.4. The aggregated grid model is shown in Figure 3.5. The sources, storage elements and loads are aggregated to form an equivalent DC voltage (V_{ag}) source and resistor (R_{ag}).

The transmission line connecting the device to the grid is simply modelled as a resistor in series with the source or storage device. The series resistor R_{trx} models the losses of the wire which results in a voltage drop between the output terminals the smart devices on the grid. The inductive and capacitive elements of the transmission line are neglected in the aggregated model as they tend to short and open circuits respectively under steady state DC conditions. The shunt resistance of the transmission line has a negligible effect due to the ultra-low voltage of the system hence is omitted.

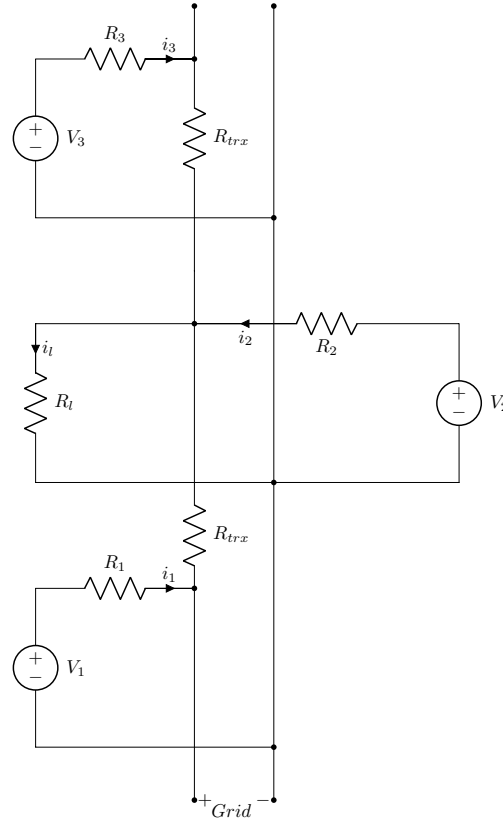
3.2 Grid Voltage Protocol

Control algorithms can be implemented without the use of a dedicated communication link. In place of a communication link, the grid voltage is utilised to infer information. A protocol dependent on the grid is developed which allows for control action to be implemented by the various devices. In order to allow the grid voltage to be an information carrier, the V_{max} and V_{min} bounds of the grid are relaxed. This relaxation implies that tight voltage regulation cannot be achieved on this grid. The developed protocol which allows smart devices to infer information is presented in Figure 3.6.

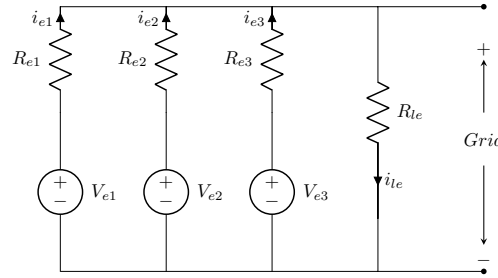
Smart solar panels have two modes of operation: MPPT mode and production curtail mode. In MPPT mode the solar panel tracks the maximum power point of the solar panel to ensure that all available solar energy is supplied to the grid. The solar panel will continue injecting maximum power into the system until $V_{gr} = V_a$. This boundary informs the solar device that the grid is stable at the current power being supplied. The solar device is required to maintain this power rating even if additional solar energy is available. The control algorithm for the smart solar panel attempts to drive its output voltage (V_{gr}) to voltage level V_a .

Smart batteries have two modes of operation: grid support mode and storage mode. In the storage mode the battery stores energy when there is a surplus. This energy is discharged when the smart battery is supporting the grid. The boundary voltage V_b determines the crossover between the two operational modes of the smart battery. The asymmetry between the nominal points of the solar (V_a) and battery (V_b) devices ensures that the solar panel has the highest priority in supplying loads. The battery will only support the grid when the solar devices are unable to meet the load demand.

Restart and shut-down modes are common to both generation and storage devices. The shut-down mode is responsible for protection against over and under voltage



(a) Three sources/storage devices (V_1 , V_2 and V_3) with internal resistances (R_1 , R_2 and R_3) connected to a resistive load R_L through a common bus with transmission losses R_{trx} .



(b) Diagrammatic simplification of Figure 3.4a

Figure 3.4: A possible version of the PeCo grid containing multiple sources, storage and load elements.

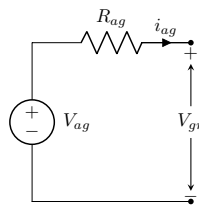


Figure 3.5: An aggregated model of the PeCo grid shown in Figure 3.4 reduced to a Thevenin equivalent where the smart battery connects at V_{gr} .

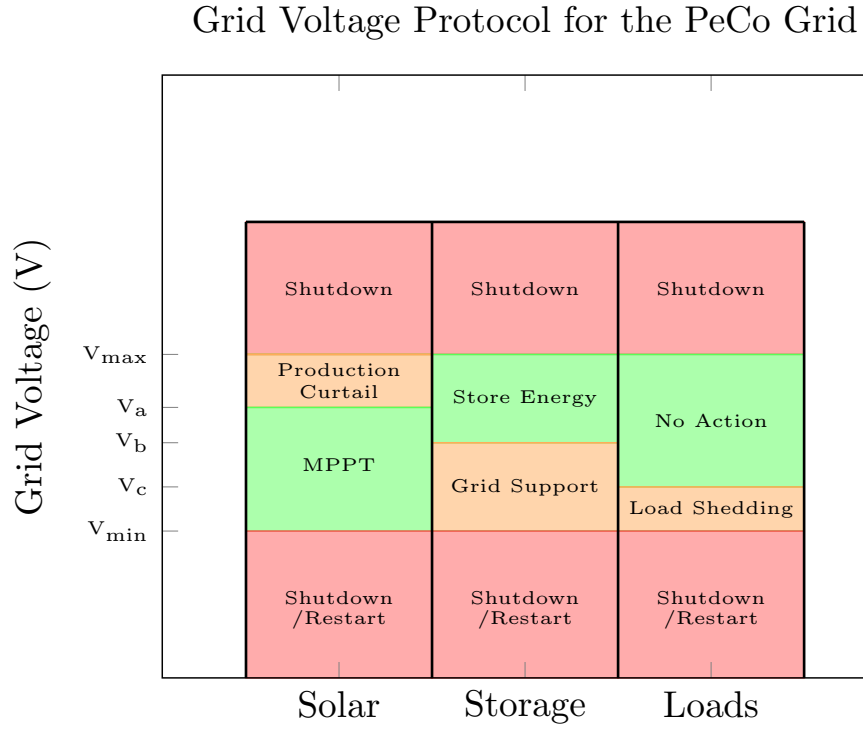


Figure 3.6: Grid voltage protocol used by the smart devices to select modes of operation.

fault conditions. From Figure 3.6 it can be seen that both modes operate within the same voltage band. However, it must be noted that they can not co-exist at the same time on the same device. They are sequential modes, where the next mode is the inverse of the current mode. This toggling between the two modes occurs until the system comes out of the fault condition.

A limitation of this protocol is that V_{gr} is affected by the transmission line connecting the smart device to the grid. The voltage drop due to the line resistance (R_{trx}) can result in incorrect information inference if the transmission line losses are high. Equation (3.1) shows the DC resistance of the transmission line where $\rho [\Omega.m]$ is the resistivity of the material, $l [m]$ is the length of the cable, and $A [m^2]$ is the cross-sectional area. This limitation can be mitigated by the usage of thicker cables or decreasing the length of the transmission line.

$$R_{trx} = \rho \frac{l}{A} \quad (3.1)$$

3.3 System Scaling

The power of the system (P_{max} [W]) is given by equation (3.2) where a is the number of generation devices and b is the number of storage devices on the grid. The operational region of the storage and generation devices is shown in Figure 3.7. Each device is bounded to operate within V_{min} and V_{max} . The device is able to supply a maximum current of $\pm i_{max}$. The addition of a new device will increase the overall power of the system illustrated in Figure 3.7. As the voltage remains bounded and the peak power capability increases, the maximum current that the system can supply increases. When a new generation device is incorporated into the grid the maximum current limit (i_{max}) slides to the right of the operational region shown in Figure 3.7. Adding more storage elements results in $-i_{max}$ sliding to the left and i_{max} sliding to the right. This sliding action is automatically achieved when a new smart element is plugged into the grid.

$$P_{max} = \sum_{n=1}^a P_n(storage) + \sum_{k=1}^b P_k(generation) \quad (3.2)$$

The usage of an ultra-low voltage grid requires high currents to achieve high power capabilities. Due to the high currents, thick cables are required in order to ensure that there low transmission losses due to the cable. The thickness of the cable limits the amount of current that can be passed through the centre bus topology illustrated in Figure 3.1. This limits the extent to which the system can be scaled due to current congestion on the central bus.

A method to reduce this congestion is to utilise a decentralised bus as shown in Figure 3.8. The PeCo grid achieves this decentralised bus by the use of three ports connected to V_{gr} . This three-port strategy results in a scalable *Ad-Hoc* architecture with a de-centralised DC bus. The peak power of the system is also limited by the manner in which the devices are interconnected. The power rating of the system can be increased by trying to ensure that the loads are scattered amongst the source and storage elements and are not all connected through a single port or connection point.

3.4 Conclusion

The PeCo grid's nominal operating voltage of 12 V allows for the leveraging of currently available appliances but this comes with the distinct disadvantage of high

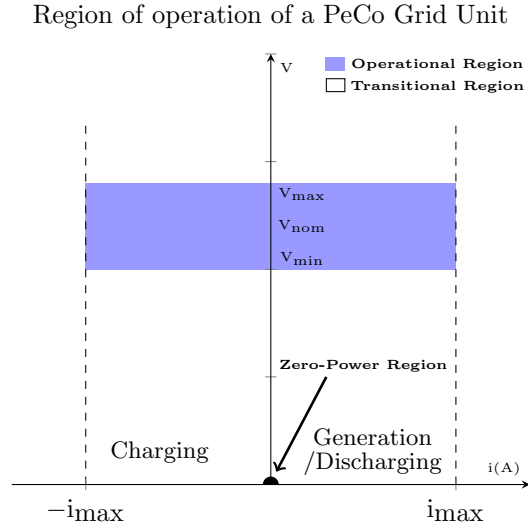


Figure 3.7: Operational region of storage and generation devices on the PeCo grid.

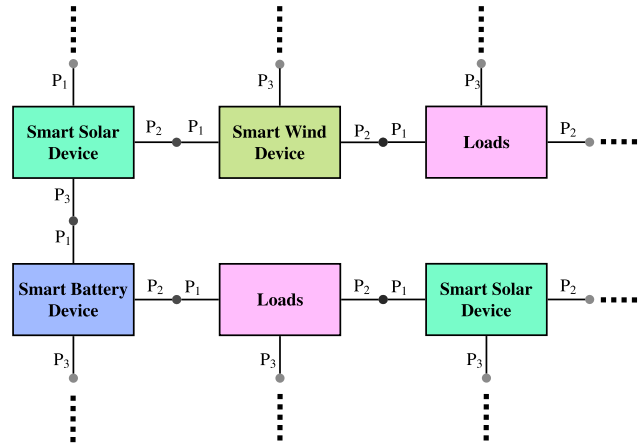


Figure 3.8: Scalability of the PeCo grid using a three port configuration.

currents required for high power. The system achieves autonomous control on the grid through a developed protocol which infers information from the grid voltage. The limitation when using this protocol is the voltage drop of the transmission line cable which could potentially result in the possibility of misinformation.

Smart battery elements are modelled simply by using a Thevenin voltage with a variable resistor. Similarly multiple, devices on the grid can be aggregated to form an equivalent Thevenin network. This chapter provides the abstract model for a smart battery to interface with the PeCo grid. Chapter 4 reviews models for a passive lead-acid battery. These models provide an insight into the required transformation for the passive lead-acid battery to exhibit the behaviour of a smart battery.

Chapter 4

Lead-Acid Battery

Energy harvested from solar panels is stored chemically through the use of lead-acid batteries. The lead-acid battery is preferred over other battery technologies due to its modularity and low cost. Equivalent models are reviewed to characterise the behaviour of this battery technology.

4.1 Battery Models

As lead-acid batteries are electrochemical devices, there exists electrical and chemical models that capture the behaviour of this battery [114–119]. Chemical models utilise complex equations to describe the behaviour of the battery whilst electrical models use simpler circuit models. The component values of the electrical models are obtained from curve fitting data gathered from testing procedures [117]. Curve fitting is performed as the values are dependant on the construction and manufacturing processes involved. Since each manufacturer utilises their own methods the component values used in electrical models are battery specific and can not be generalised.

4.1.1 Simple Battery Model

The ideal battery shown in Figure 4.1a has a constant voltage with no current limit. This behaviour is not realistic as real batteries can only provide a limited amount of current due to the conduction losses and finite electrolytes within the battery. These losses can be modelled as a series resistor as shown in Figure 4.1b. This improved model limits the maximum power the battery can provide.

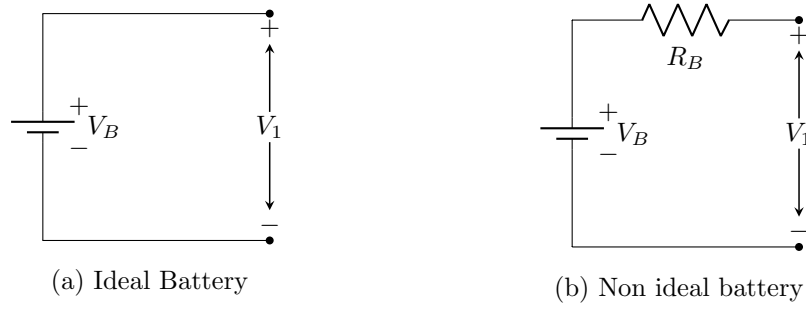


Figure 4.1: Simple battery models.

4.1.2 Thevenin Battery Model

The discharge curve of a lead-acid battery undergoing constant current discharge is shown in Figure 4.3. From this curve it is noted that the model discussed in Section 4.1.1 does not capture the nonlinear behaviour of the lead-acid battery. An alternative to the simple model presented earlier is the commonly used Thevenin battery model [118–120] shown in Figure 4.2. This model captures the RC and overvoltage behaviour that occurs during loading and unloading of the battery. In addition to capturing the above-mentioned characteristics, this model improves upon the simple model as the voltage source (V_{oc}) is not constant but is dependant on the State of Charge (SOC) of the battery. The linear relationship between the SOC and the Open Circuit Voltage (OCV) of the battery is shown in Figure 4.4. Although the Thevenin model captures the nonlinear behaviour, its drawback is the use of fixed components. In reality, these parameters vary with time and are functions of:

- Battery age
- SOC
- Temperature

4.1.3 Dynamic Models

Dynamic models are used to capture the time varying properties of the battery. Common dynamic models are presented by Shepherd [114], Manegon [121] and Coppetti [122]. The work done by Coppetti *et al.* in [122] provides the most comprehensive of the three models. Coppetti's work captures the non-linear dynamic behaviour using equations (4.1) to (4.9). An advantage of this model over the models presented

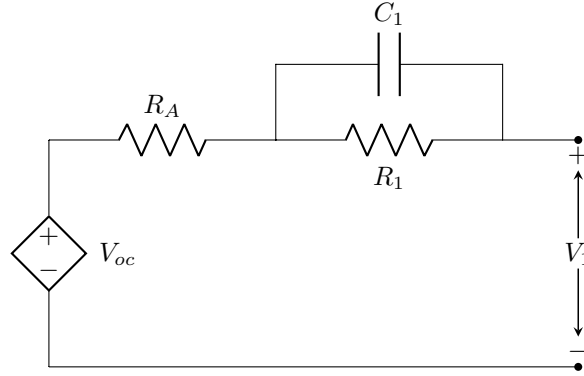


Figure 4.2: Nonlinear Thevenin equivalent model of a lead-acid battery.

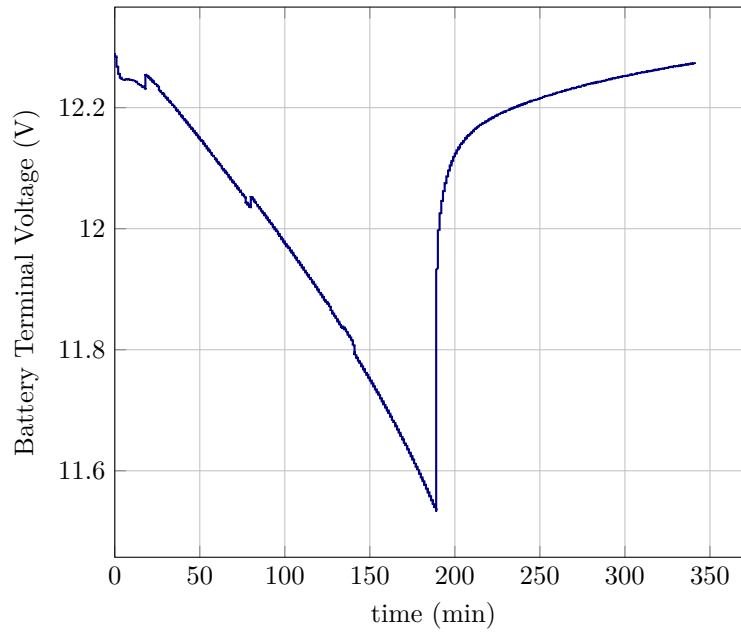


Figure 4.3: Lead-acid battery discharge characteristic of a 7 Ah battery obtained experimentally as described in Appendix H where the battery is discharged under constant current and the load is disconnected at 190 min.

earlier in Sections 4.1.1 & 4.1.2 is its general nature allowing it to be applied without requiring the rigorous battery testing as is common with electrical models [122]. The Coppetti model describes the operation of the battery using a charge mode (equations (4.5) to (4.9)) and a discharge mode (equations (4.1) to (4.4)). The discharge equation for a single cell is given by:

$$V_{DC} = [2.085 - 0.12(1 - SOC)] - \frac{I}{C_R} \left(\frac{4}{1 + I^{1.3}} + \frac{0.27}{SOC^{1.5}} + 0.02 \right) (1 - 0.007\Delta T) \quad (4.1)$$

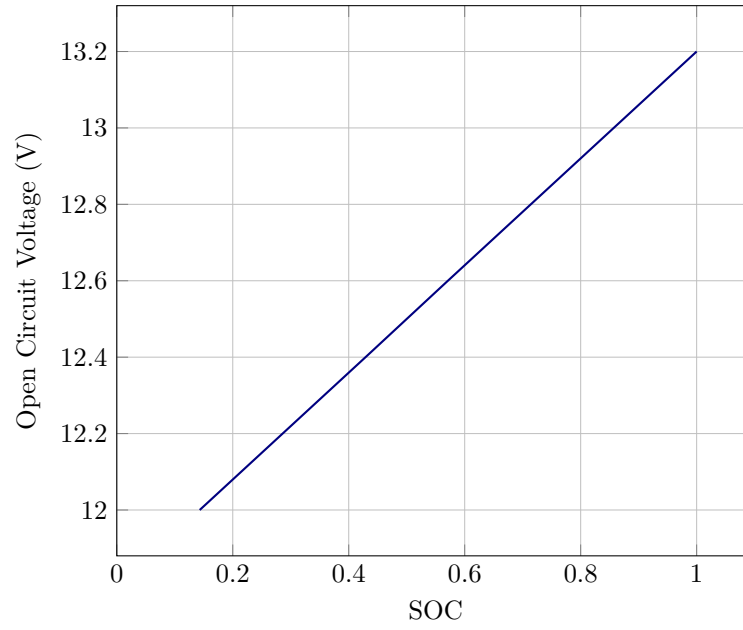


Figure 4.4: Open circuit voltage vs SOC of a 7 Ah lead acid battery obtained experimentally as described in Appendix H where the battery is discharged under a constant current of 1 A and the SOC is computed using Coulomb counting.

$$\Delta T = T_c - 25 \quad (4.2)$$

$$SOC = 1 - \frac{Q}{C_R} \quad (4.3)$$

$$Q = I_d t_d \quad (4.4)$$

where SOC is the current state of charge, C_R [Ah] is 10 or 20 hour rated capacity specified by the manufacturer, I [A] is the discharge current, T_c [°C] is the battery temperature and Q [Ah] is the charge usage. The discharge equations factor in temperature, SOC and battery loading.

The charge equations capture the behaviour of the battery during: the charge phase where the battery does not experience gassing (equation (4.5)) and the overcharging phase where the battery experiences gassing (equation (4.8)). The charge equations are given by:

$$V_{CH} = [2 + 0.16 SOC] + \frac{I}{C_R} \left(\frac{6}{1 + I^{0.86}} + \frac{0.48}{(1 - SOC)^{1.2}} + 0.036 \right) \quad (4.5)$$

$$V_G = [2.45 + 2.011 \ln(1 + \frac{I}{C_R})](1 - 0.002\Delta T) \quad (4.6)$$

$$V_{EC} = [2.24 + 1.97 \ln(1 + \frac{I}{C_{10}})](1 - 0.002\Delta T) \quad (4.7)$$

$$V_{OC} = V_G + (V_{EC} - V_G)[1 - \exp(\frac{Ah_{Restored} - 0.95C}{I_{ch}}\tau(t))] \quad (4.8)$$

$$\tau = \frac{17.3}{1 + 852(\frac{I}{C_R})^{1.67}} \quad (4.9)$$

4.2 Lead-Acid Operational Considerations

The levels to which the battery is charged and discharged play an important role in battery management. If the lead-acid battery continuously experiences a high Depth of Discharge (DOD), the life expectancy of the battery is significantly reduced.

During the charging phase, it is important to ensure that the battery does not undergo overcharging as this reduces the electrolytic content within the battery resulting in life expectancy reduction of the battery. The efficiency factor of stored energy versus energy applied to the battery must also be considered during the charging process. Reference [122] defines the charge efficiency as:

$$\eta_e = 1 - \exp[\frac{a}{I/I_{10} + b}(SOC - 1)] \quad (4.10)$$

where a and b are found from curve fitting the batteries and are battery specific. The various models show the role of temperature and how it affects the performance of the battery. High temperatures result in electrolytic depletion which reduces battery life.

4.3 Conclusion

The simple battery models do not fully capture the behaviour of the lead-acid battery. An alternative to the simple model is the commonly used Thevenin model which is

able to capture the battery's nonlinear behaviour but relies on the model components being constant. In reality, the lead-acid battery is a nonlinear and time-varying device that changes as a function of SOC, age and temperature. These factors are taken into consideration in dynamic battery models such as the Coppetti model. In order to interface the nonlinear lead-acid battery to the PeCo grid discussed in Chapter 3, a DC-DC converter is required to transform it to the required variable DC voltage source and resistor. Chapter 5 investigates the dual active bridge bi-directional DC-DC converter.

Chapter 5

Dual Active Bridge

The Dual Active Bridge (DAB) is a bi-directional DC-DC converter topology that is capable of high current transfer. A typical DAB can be seen in Figure 5.1. The converter consists of two H-bridges that are magnetically coupled through a high-frequency transformer. Energy storage is done in the leakage inductor L_s . The switches in the H-bridge can either be MOSFETs or IGBTs. The usage of eight switching devices results in a reduction of conduction losses.

Considering the components shown in Figure 5.1 as ideal, the equivalent circuit depicted in Figure 5.2 is obtained. Each H-Bridge is an AC voltage source while the transformer and leakage inductor are collapsed to the single inductor L_s . From this circuit, we note that this is the classical power transfer mechanism used in bi-directional AC systems. By controlling the phase delay (α) between the primary and secondary voltage sources the amount of power transferred to either voltage source can be controlled. This is known as phase shift modulation and is the simplest

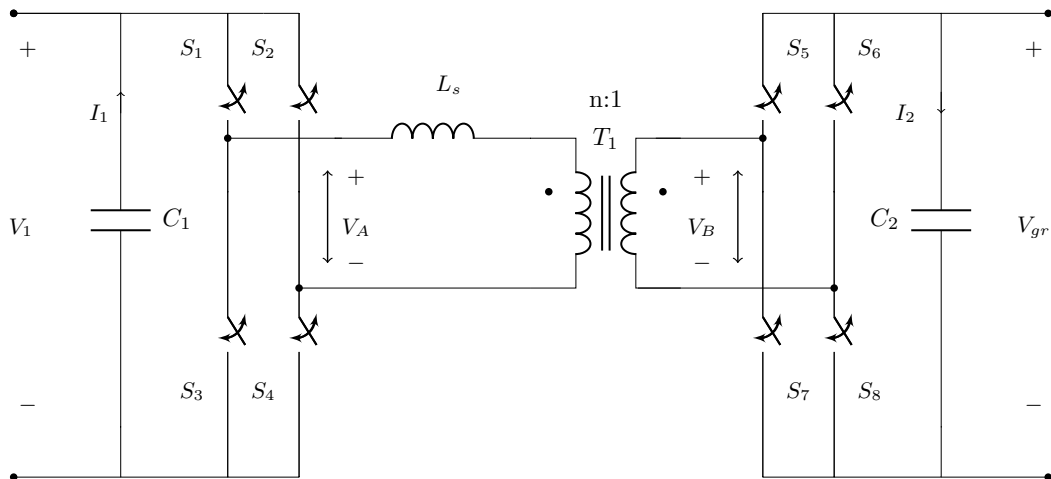


Figure 5.1: Dual active bridge DC-DC converter topology.

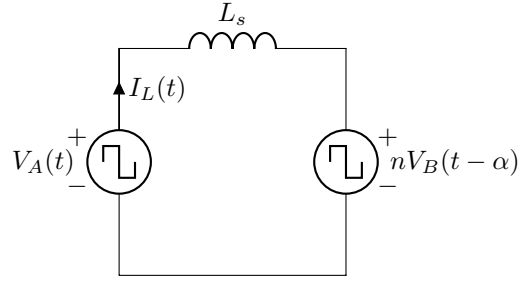
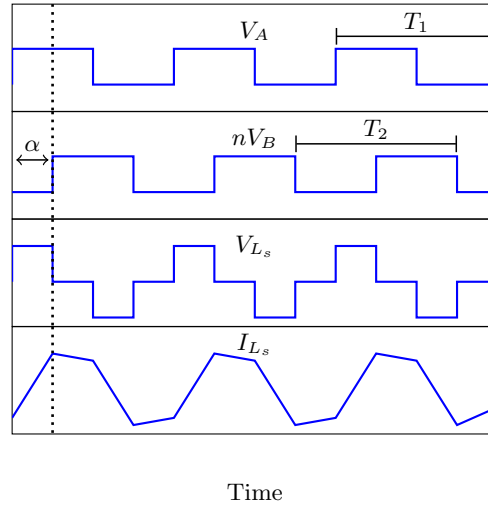


Figure 5.2: Lossless model of the DAB.

Figure 5.3: Operational waveforms for the DAB using phase shift modulation where T_1 and T_2 are the periods of the square waves and $T_1 = T_2$.

of the DAB modulation schemes. Other modulation schemes such as triangular modulation or trapezoidal modulation schemes discussed in [66] work on the principle of manipulating the phase shift between the bridges and the duty cycle of the square waves to achieve triangular and trapezoidal current waveforms through the inductor. These schemes result in lower RMS currents in comparison to phase shift modulation but come with an increase in complexity [66, 67].

Phase shift modulation is achieved by controlling the square waves V_A and V_B shown in Figure 5.3. Delaying V_B by some time α , a differential voltage V_{L_s} is applied to the leakage inductor where $V_{L_s} = V_A - V_B$. The differential voltage V_{L_s} causes the AC current I_{L_s} to flow through the leakage inductor. The direction of power flow occurs from V_A to V_B if V_B is the lagging source. Power flow can be reversed i.e. from V_B to V_A by making V_B the leading voltage source. The magnitude of the transferred power is controlled by the duration of α .

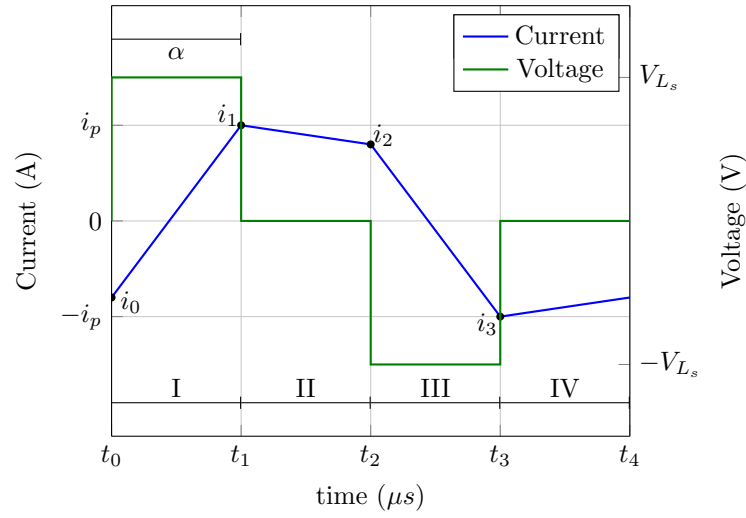


Figure 5.4: Inductor current and voltage waveforms for phase shift modulation over one switching period T_S .

5.1 Lossless Dual Active Bridge

The square waves V_A and V_B are given by equation (5.1) and equation (5.2) where V_1 and V_{gr} are the respective DC voltages of the battery terminals and grid connection. The square waves have a period of T_s and are symmetrical about $\frac{T_s}{2}$.

$$V_A(t) = \begin{cases} V_1 & 0 < t < \frac{T_s}{2} \\ -V_1 & \frac{T_s}{2} < t < T_s \end{cases} \quad (5.1)$$

$$nV_B(t - \alpha) = \begin{cases} nV_{gr} & \alpha < t < \frac{T_s}{2} + \alpha \\ -nV_{gr} & \frac{T_s}{2} + \alpha < t < T_s + \alpha \end{cases} \quad (5.2)$$

Consider the leakage inductor current (I_{L_s}) and voltage (V_{L_s}) waveforms for the lossless DAB as depicted in Figure 5.4. The voltage can be related to the inductor current by using equation (5.3) where i_0 is the initial current of the inductor.

$$\begin{aligned} V_{L_s} &= L_s \frac{dI_{L_s}}{dt} \\ \therefore I_{L_s} &= \frac{1}{L_s} \int_0^{T_s} V_{L_s}(t) dt + i_0 \end{aligned} \quad (5.3)$$

The inductor current can be divided into four intervals over the switching period T_s . Each interval results in the switching currents shown in equations (5.4) to (5.8).

$$i_a(t) = \frac{(V_1 + nV_{gr})}{L_s} t + i_0 \quad 0 \leq t \leq t_1 \quad (5.4)$$

$$i_b(t) = \frac{(V_1 - nV_{gr})}{L_s} (t - t_1) + i_1 \quad t_1 \leq t \leq t_2 \quad (5.5)$$

$$i_c(t) = -i_a \quad t_2 \leq t \leq t_3 \quad (5.6)$$

$$i_d(t) = -i_b \quad t_3 \leq t \leq t_4 \quad (5.7)$$

$$I_{L_s} = i_a(t) + i_b(t) + i_c(t) + i_d(t) \quad (5.8)$$

Due to the half cycle symmetry of the inductor current waveform $i_o = -i_b(\frac{T_s}{2})$ and $i_1 = i_a(t_1)$. Solving equations (5.9) & (5.10) simultaneously the initial condition i_o is solved for in equation (5.11).

$$i_0 = -\frac{V_1 - nV_{gr}}{L_s} (t_2 - t_1) - i_1 \quad (5.9)$$

$$i_1 = \frac{V_1 + nV_{gr}}{L_s} t_1 + i_0 \quad (5.10)$$

$$i_0 = \frac{T_s}{4L_s} [nV_{gr}(1 - 4\alpha) - V_1], \quad \alpha = \frac{t_1}{T_s} \quad (5.11)$$

As I_{L_s} has been defined as a function of the DC voltage sources and α , the average power transfer to the DC sources can be obtained from equation (5.12).

$$\begin{aligned} P = P_{gr} = P_1 &= \frac{1}{t_2} \int_0^{t_2} V_A(t) I_{L_s}(t) dt \\ &= \frac{V_1}{t_2} \int_0^{t_2} I_{L_s}(t) dt \\ &= \frac{\alpha V_1 nV_{gr}(1 - 2\alpha)}{f_s L_s} \end{aligned} \quad (5.12)$$

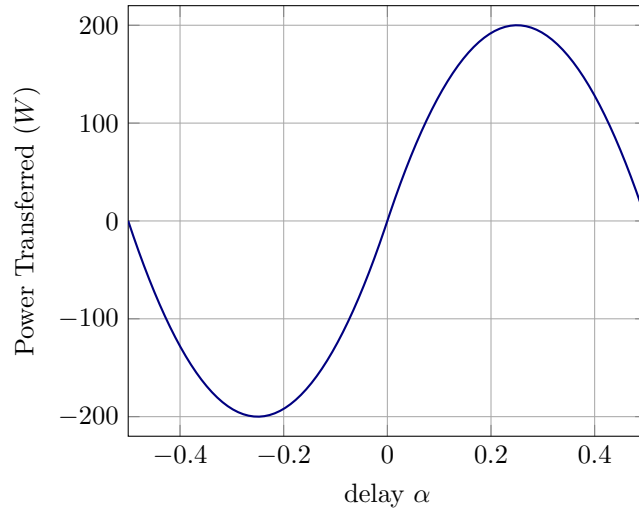


Figure 5.5: Power transfer to V_{gr} when varying α as per equation (5.12) for $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ and $V_{gr} = 12 \text{ V}$.

The power transfer as a function of the delay α is shown in Figure 5.5. From Figure 5.5 the maximum power transfer occurs at $\alpha = 0.25$. Substituting $\alpha = 0.25$ into equation (5.12) the maximum leakage inductance required for power transfer is:

$$L_s \leq \frac{V_1 n V_{gr}}{8 f_s P_{max}} \quad (5.13)$$

The power transfer measured on the developed DAB in Appendix C is shown in Figure 5.6. From this figure, it is observed that the power transferred to V_{gr} is less than that of the ideal model described by equation (5.12). This is to be expected as the ideal model does not account for losses in the DAB converter. An accurate model for power transfer is required as this is utilised by the control algorithms in Chapter 6.

5.2 Lossy Dual Active Bridge

The effect of losses on the DAB can be modelled using the circuit shown in Figure 5.7. The coil losses of the leakage inductor and transformer are lumped as a resistor in series with the leakage inductor L_s . The closed form solution for this system has been derived [66, 82] and is shown in equation (5.14). The complexity of this solution results in an increase in the required computational power which is undesirable for implementation on a microcontroller. An alternative to Krismer's loss derivation

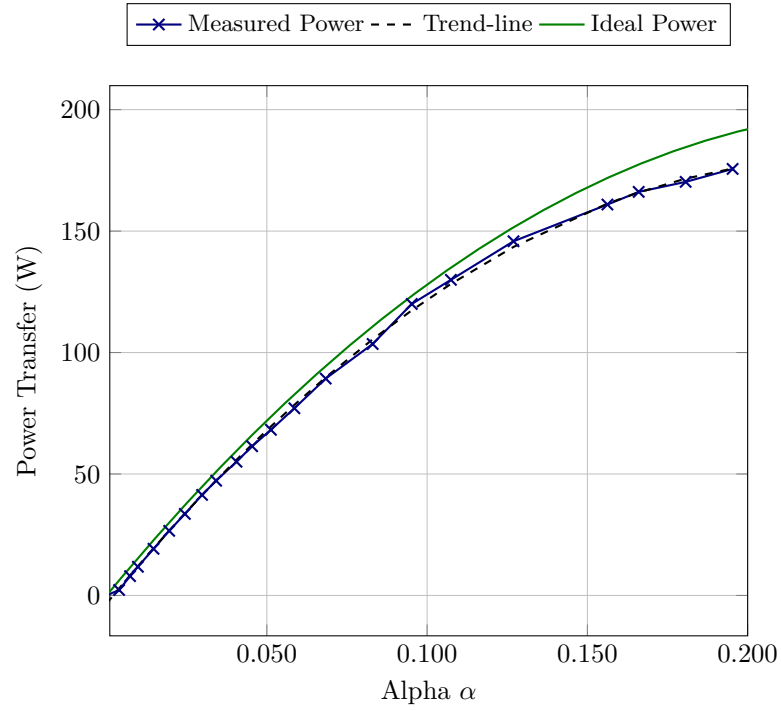


Figure 5.6: Measured power transfer on the experimental prototype to V_{gr} when varying α for $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ and $V_{gr} = 12 \text{ V}$.

is work done in [82]. This model takes into account switching losses and source resistances but is of greater complexity than Krismer's work.

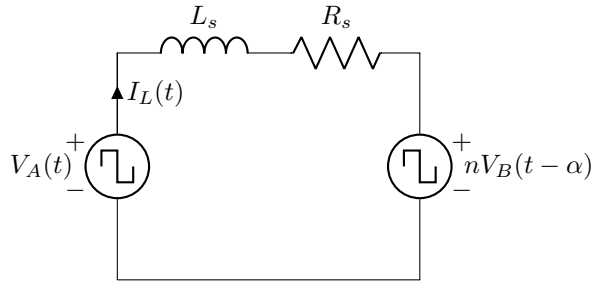


Figure 5.7: Lossy DAB model where R is the lumped coil resistance.

$$\begin{aligned}
 P_{Loss} = & \left\{ \left(1 - 4\tau f_s \tanh\left[\frac{1}{4\tau f_s}\right] \right) \left(\frac{V_1^2}{R} + \frac{V_{gr}^2}{R} \right) - \frac{2V_1 V_{gr}}{R} \left(1 - \frac{|2\phi|}{\pi} + 4\tau f_s \sinh\left[\frac{|\phi|}{2\pi\tau f_s}\right] \right) \right. \\
 & \left. + \frac{8V_1 V_{gr} \tau f_s}{R} \left(\cosh\left[\frac{|\phi|}{2\pi\tau f_s}\right] \tanh\left[\frac{1}{4\tau f_s}\right] \right) \right\} \text{sgn}(\phi)
 \end{aligned} \tag{5.14}$$

where $\tau = RL$ and $\phi = \frac{t_1}{2\pi f_s}$

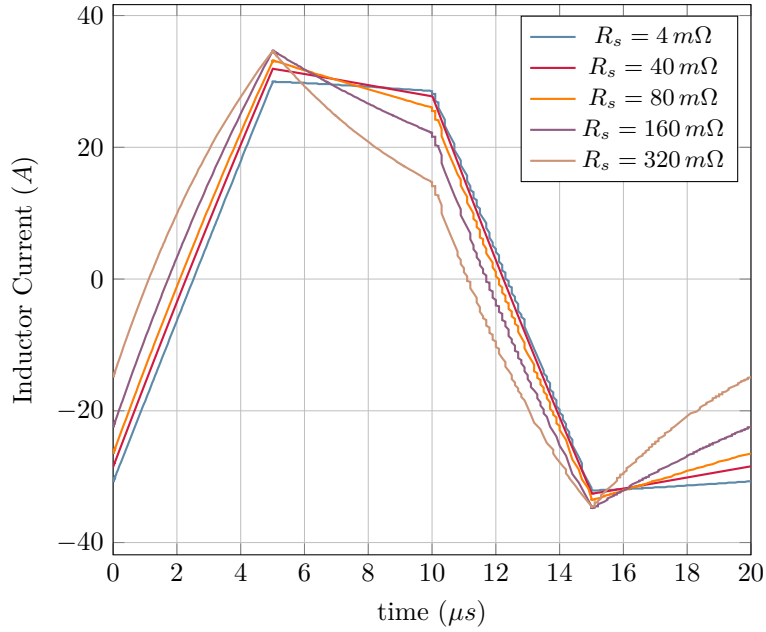


Figure 5.8: Simulated inductor current when the series losses are varied.

An alternative estimation method is required that is less computationally burdensome. Using the Spice simulation developed in Appendix B the effects of the losses is captured in Figure 5.8. By keeping the leakage inductance L_s constant and varying the series loss R_s , it is observed that as $R_s \rightarrow X_s$ (where X_s is the impedance at the switching frequency) the current waveform becomes non-linear as the voltage across the leakage inductor V_{L_s} is no longer the rectangular waveform shown in Figure 5.3.

If it is ensured that the designed dual active bridge abides by the following constraint:

- $R_s \ll X_s = \omega L_s$

the voltage waveform appearing across the leakage inductor is approximately the same as that of the ideal waveform shown in Figure 5.3 as $V_{R_s} \ll V_{L_s}$. This results in the current flowing through the leakage inductor to be approximately equal to that of the ideal current derived in equation (5.8).

The losses of the coil is driven by an AC current therefore the RMS current is used to compute the equivalent DC losses. From equation (5.8) and the half cycle symmetry

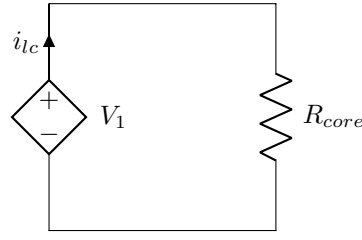


Figure 5.9: Core loss model for the DAB.

of the inductor current waveform the RMS current is defined by:

$$\begin{aligned}
 I_{L_{RMS}} &= \sqrt{\frac{2}{T_s} \int_0^{T_s} I_L(t)^2 dt} \\
 &= \sqrt{\frac{1}{T_s} \left(\int_0^{t_1} i_a(t)^2 dt + \int_{t_1}^{t_2} i_b(t)^2 dt \right)} \\
 &= \sqrt{\frac{\alpha^2 V_1 V_{gr} (48 - 64\alpha) + (V_1 - V_{gr})^2}{48 L_s^2 f_s^2}}
 \end{aligned} \tag{5.15}$$

Using equation (5.15) the conduction losses is expressed using the RMS current as:

$$P_{conductionLoss} \approx I_{L_{RMS}}^2 (R_{coil} + 2 R_{DS_{on}} + 2 \frac{R_{DS_{on}}}{n^2}) \tag{5.16}$$

where $R_{coil}[\Omega]$ is the combined AC resistance of the transformer and inductor coils and $R_{DS_{on}}[\Omega]$ is the on-resistance of the switching devices.

In addition to the conduction losses, the core losses need to be accounted for. The core losses are modelled by the use of a shunt resistor connected to the dependant DC voltage source as shown in Figure 5.9. The power dissipated by the core is expressed in equation (5.17).

$$P_{shunt} = \frac{V_1^2}{R_{shunt}} \tag{5.17}$$

where $R_{shunt}[\Omega]$ is obtained experimentally by measuring the average DC voltage and current of the input port at zero power transfer with no loading on the output port.

The total loss of the DAB converter is expressed as per equation (5.18). Using equations (5.12) & (5.18) the transferred power to a port is expressed as shown in

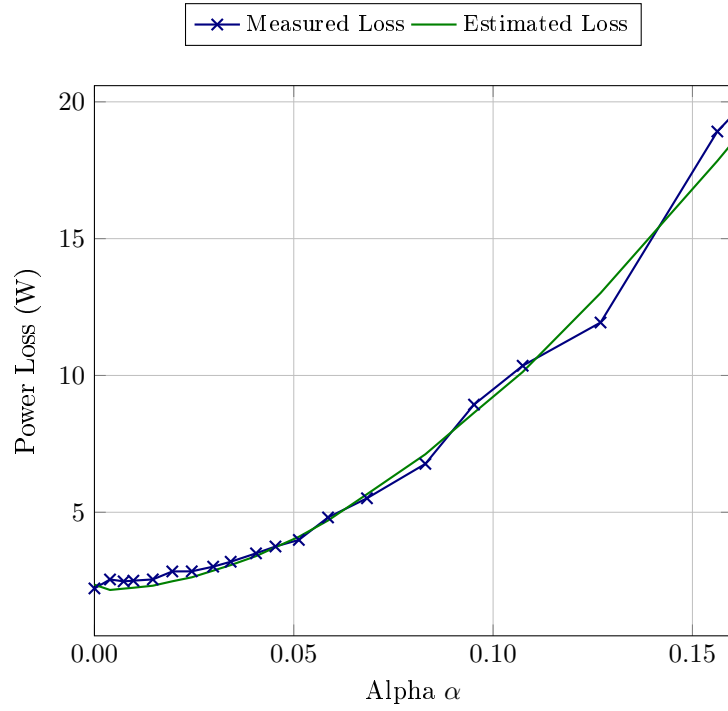


Figure 5.10: Experimentally measured and estimated power loss using equation (5.18) for $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ and $V_{gr} = 12 \text{ V}$.

equation (5.19).

$$P_{LossTotal} = P_{core} + P_{shunt} \quad (5.18)$$

$$P_{trans} = P_{ideal} - P_{loss} \quad (5.19)$$

Figure 5.10 compares the losses estimated using equation (5.18) to losses measured by the prototype DAB in Appendix C. Figure 5.10 shows that the loss estimator is able to estimate the power loss within 5%. As α increases, the RMS current increases and the voltage drop across the resistance R_s has a greater influence on the RMS current. This increase in V_{R_s} results in the RMS current from the lossless model to deviate from the RMS current in a lossy DAB converter. Since the loss estimator is based upon the ideal RMS current the loss estimator deviates from the measured current. This technique allows the power transfer to be computed with an accuracy of 5% without the use of a current sensing technique and is purely voltage based.

Table 5.1: DAB Specifications for the PeCo Grid

Description	Value	Description	Value
V_{1min}	10 V	V_{1nom}	12 V
V_{1max}	14 V	V_{grmin}	10 V
V_{grnom}	12 V	V_{grmax}	14 V
P_{max}	150 W	R_s	40 mΩ
f_s	50 kHz		

5.3 Selection of L_s

The leakage inductor is upper bounded as shown in equation (5.12). The lower bound of the inductor is constrained by the loss R_s as discussed in Section 5.2. The required inductance to achieve a particular power rating is:

$$\frac{10R_s}{2\pi f_s} \leq L_s \leq \frac{nV_1V_{gr}}{8f_sP_{max}}. \quad (5.20)$$

This expression ensures that $R_s \ll X_s$ which allows for the application of the lossless estimation technique discussed above.

The designed DAB converter is required to meet the PeCo grid specifications summarised in Table 5.1. Using the nominal specifications, the required inductance L_s to achieve a power rating 150 W is given by: $1.2 \mu\text{H} \leq L_s \leq 2.4 \mu\text{H}$.

The plots in figures 5.11 to 5.13 shows how the inductance affects the RMS current and the delay α . From these figures, it can be seen that as the inductance decreases the RMS current and α decrease. A lower RMS current is attractive as it results in lower losses. As α decreases a higher resolution is required if the modulation scheme is implemented using a digital device such as a micro-controller.

Factoring in the resolution constraint of the selected micro-controller in Appendix C an inductance of $1.8 \mu\text{H}$ was selected. Including the effects on α and RMS current as a function of inductance, Figures 5.11-5.13 illustrate the effect that a voltage mismatch between the input and output port has on the RMS current of the device. This change in RMS current directly affects losses and hence the efficiency of the device at different voltage levels.

The power transfer of the DAB from Appendix C is shown in Figure 5.14 which

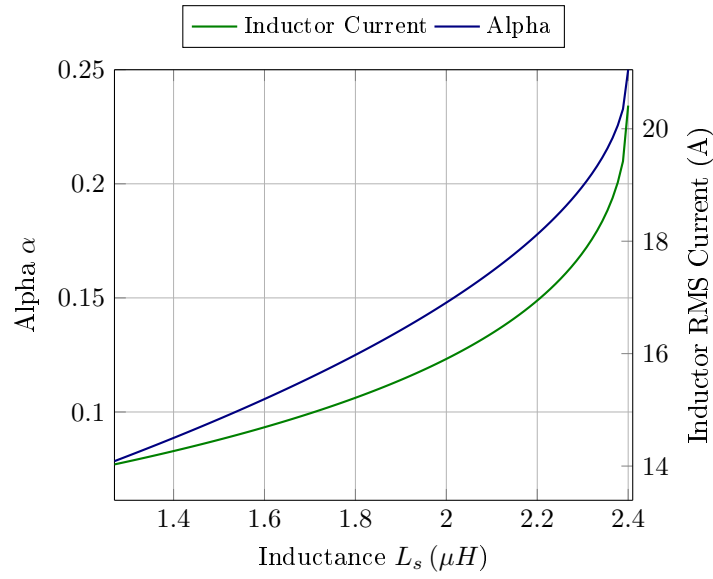


Figure 5.11: Ideal inductor current and delay α for $P = 150\text{ W}$ when $V_1 = 12\text{ V}$ & $V_{gr} = 12\text{ V}$

shows the symmetrical bi-directional nature of the converter. The efficiency of the device is depicted in Figure 5.15. Figure 5.15 shows that the device is able to achieve an efficiency of 90% above 40 W but has a low efficiency when lightly loaded.

5.4 Conclusion

The design of DAB revolves around the selection of the inductor L_s . Following the design procedure and guidelines outlined in this chapter, a DAB capable of transferring 150 W at 12 V was built and tested. The designed converter has an efficiency of 90% at full loading. The design process also allows for a simple and effective loss estimation technique developed to be implemented. This technique is purely voltage based and does not require the usage of a current sensor. The successful design of the DAB prototype establishes a platform for bi-directional power processing. This platform can now be used to manage the interaction between the lead-acid battery and the PeCo grid. The manner in which these interactions occur is determined by the control algorithms developed in Chapter 6.

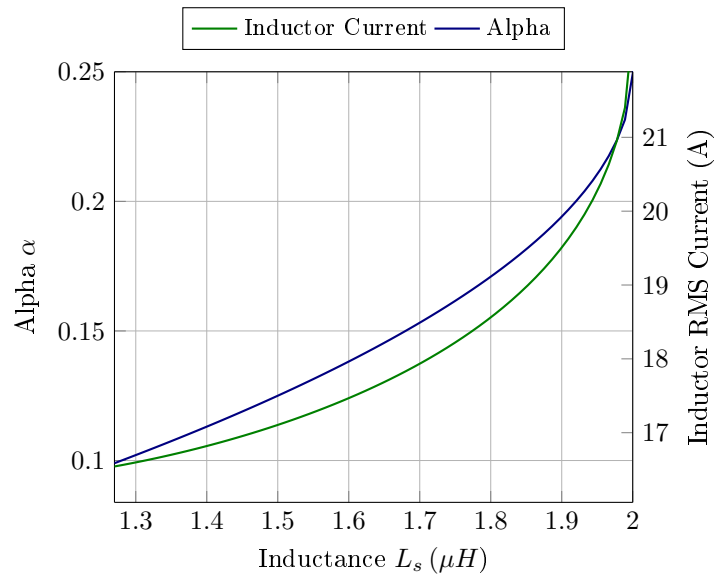


Figure 5.12: Ideal inductor current and delay α for $P = 150$ W when $V_1 = 14$ V & $V_{gr} = 12$ V.

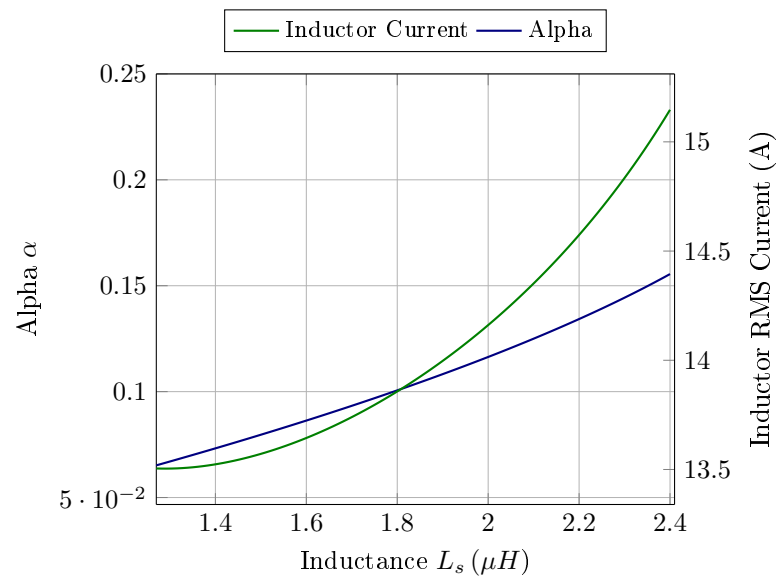


Figure 5.13: Ideal inductor current and delay α for $P = 150$ W when $V_1 = 10$ V & $V_{gr} = 12$ V.

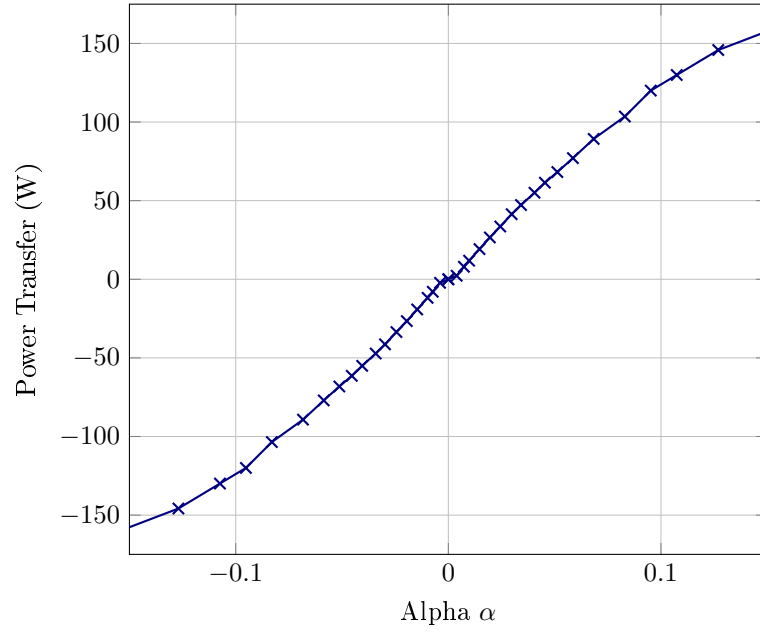


Figure 5.14: Measured DAB power transfer of built experimental prototype when $L_s = 1.8 \mu\text{H}$, $V_1 = 12 \text{ V}$ & $V_{gr} = 12 \text{ V}$ when loaded with a varying resistor.

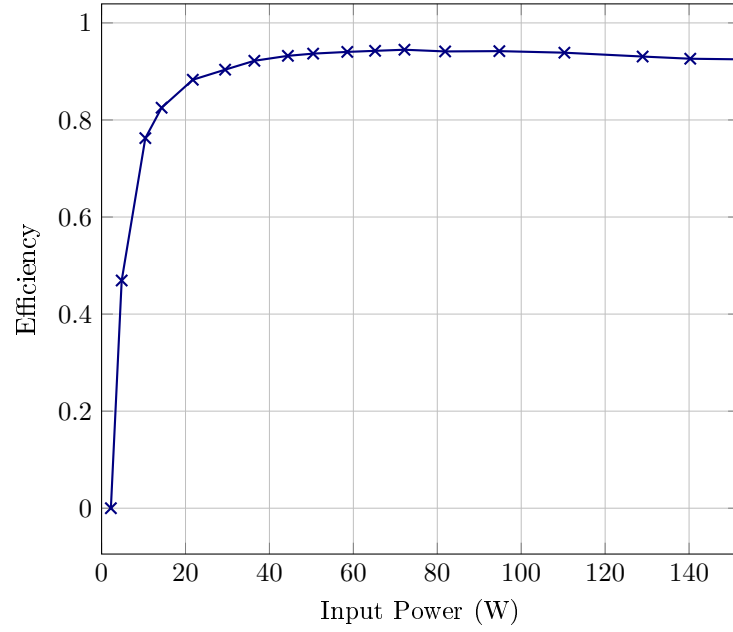


Figure 5.15: Measured efficiency of the experimental prototype for $L_s = 1.8 \mu\text{H}$ when $V_1 = 12 \text{ V}$ & $V_{gr} = 12 \text{ V}$.

Chapter 6

Control Algorithm

The control algorithms required to interface a lead-acid battery with the PeCo grid is discussed in this chapter. The interaction between the lead-acid battery, the DAB converter and the MCU is shown in Figure 6.1. Control signals sent from the MCU to the DAB are based on the PeCo grid terminal voltage V_{gr} and the lead-acid battery terminal voltage V_{bat} .

The objective of the controller is to stabilise the grid and manage the battery. These objectives are accomplished by controlling the power flow to and from the battery using the DAB converter developed in Chapter 5. The dynamics of the battery and DAB are managed in a manner such that the equivalent circuit behaves as a variable voltage source and resistor as shown in Figure 3.3. To establish the required control action, identification of the commonly occurring events are required.

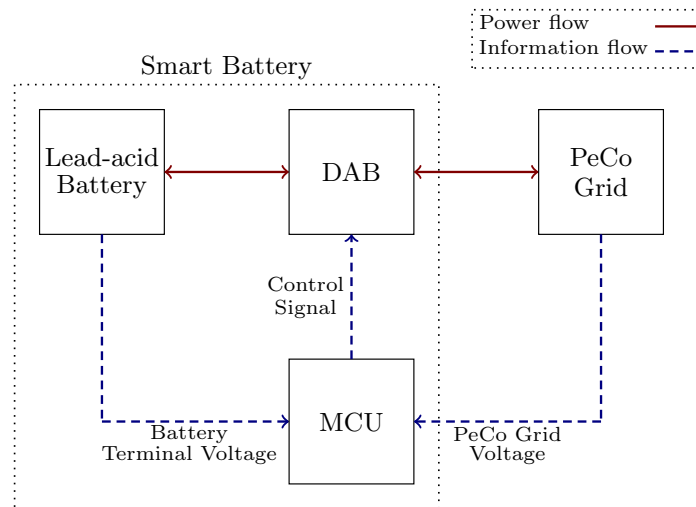


Figure 6.1: Block diagram of the smart battery showing key components and their interactions.

6.1 PeCo Grid Scenarios

The aggregated model of the grid developed in Chapter 3, repeated in Figure 6.2, is used to derive the grid scenarios. The developed algorithms are required to maintain a stable grid voltage as defined in Chapter 3.

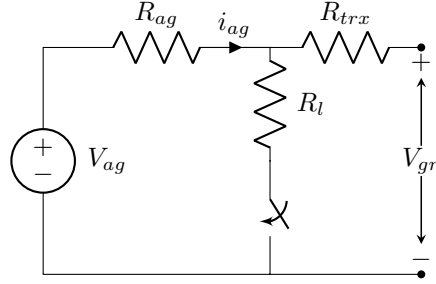


Figure 6.2: Grid model of the PeCo grid used to test the smart battery which connects to V_{gr} .

6.1.1 No Generation on the Grid

In this instance, the smart battery is the only entity on the grid and is the simplest of the grid scenarios. Since the resistance $R_{ag} = \infty$, the smart battery establishes a grid and regulates the voltage across the lumped load resistance R_l which can vary from R_{min} to ∞ . The lower bound R_{min} is determined by the power rating of the smart battery. The smart battery must be able to stabilise the grid over the entire resistance range.

6.1.2 Lightly Loaded Grid

In this scenario $R_l = \infty$ and $V_{ag} > V_{gr}$. These conditions describe the event that occurs when there are no loads on the grid and generation devices are producing energy. Due to the load not consuming power the smart battery is required to store the generated energy. When the grid experiences this event, the aggregated current i_{ag} can vary from $0 \leq i_{ag} \leq i_{ag_{max}}$ as the generated energy fluctuates. Even though the generation current is fluctuating, the smart battery is required to keep V_{gr} stable.

6.1.3 Operational Grid

When the grid is in operation, there is generation and load consumption occurring simultaneously. The role of the smart battery is to modulate the power flow to and from the battery in a manner that ensures the grid is stabilised. This requires that the battery is able to smoothly transition from supplying power to absorbing power.

6.2 Battery Functionality

In addition to the scenarios described in Section 6.1, the smart battery is required to have additional functionalities that result in a stable and durable power system. This section identifies the functional requirements for a stable and robust power system.

6.2.1 Soft Starting

During start-up, the device raises the grid voltage which establishes a grid. A step start-up from 0 to V_{nom} is likely to result in transient behaviour on the DC grid. However, if the voltage is ramped up, the likelihood of transient voltages being introduced into the system are lower.

6.2.2 Fault Detection and Protection

Two types of faults can occur on the PeCo grid i.e: over-voltage and under-voltage faults. Under-voltage faults indicate a heavily loaded system or short circuit. During the time interval while the fault is in progress the smart battery must disconnect from the grid in order to protect the device. If all smart devices implement this disconnection procedure during faults, the power system is inherently protected. Once the fault has passed, the grid is required to automatically detect this and restart.

6.2.3 System Scaling

The device must seamlessly interface and integrate into an existing power system which could potentially consist of multiple generation and storage elements. The commissioning and integration must occur with minimal user interaction. This

process must occur automatically when the smart device is plugged into the PeCo grid.

6.2.4 Battery Management

Although the smart battery’s primary objective is grid stabilisation, the passive battery technology requires management to ensure longevity and lifespan prolongment. Battery management is responsible for tracking the SOC which prevents overcharging from occurring. To prevent over discharging the battery the DOD is monitored as there is a direct relationship between battery lifespan and DOD for lead-acid batteries.

6.3 Voltage Inference Engine

One of the key features of the PeCo grid is the absence of a dedicated communication link between smart elements on the grid. All control action is based on the grid voltage V_{gr} that each device sees at its output terminal. To achieve the characteristics discussed in Sections 6.1 & 6.2 an inference method is designed to deduce information from the grid voltage. The designed inference engine is shown in Table 6.1. The relationship between the voltage levels in the inference engine is described using the voltage line in Figure 6.3.

An over-voltage fault is triggered when the grid voltage exceeds the maximum voltage V_{max} . Similarly, a short circuit or overloading is detected when the voltage falls below or cannot be raised above the lower bound V_{min} . Three levels of health have been demarcated to provide an indicator on the current condition of the grid. Moving the grid trajectory towards the “good health band” is the desired outcome of the smart devices on the grid. Although the orange and yellow bands are less desired in comparison to the green band, the grid is still regarded as operational and will continue to function while the smart devices attempt to re-correct and move the grid voltage trajectory towards the green band. A similar approach is used to infer information from the terminals of the battery. The battery inference engine is shown in Table 6.2. A voltage below $V_{bat_{min}}$ indicates a faulty battery or no battery connection while a voltage above $V_{bat_{max}}$ indicates that the battery is experiencing overcharging.

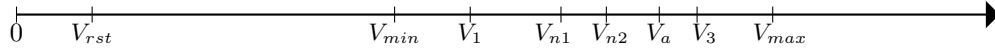


Figure 6.3: Grid voltage levels utilised for grid inference engine in Table 6.1.

Voltage (V)	Inferred Information
$0 < V_{gr} < V_{min}$	Overloaded grid or Short Circuit
$V_{rst} < V_{gr} < V_{min} \ \& \ \Delta V_{gr} > 0$	Devices restarting grid
$V_{min} \leq V_{gr} < V_1$	Grid Health: Marginally Ok
$V_1 \leq V_{gr} < V_{n1}$	Grid Health: Acceptable
$V_{n1} \leq V_{gr} \leq V_{n2}$	Grid Health: Good
$V_{n2} < V_{gr} < V_3$	Grid Health: Marginally Acceptable
$V_3 \leq V_{gr} \leq V_{max}$	Grid Health: Marginally Ok
$V_{gr} > V_{max}$	Overvoltage
$V_a \leq V_{gr} < V_{max}$	Solar energy available

Table 6.1: Grid voltage inference engine

6.4 Smart Battery as a Finite State Machine

The smart battery is modelled as a state machine to describe the actions performed to meet the objectives discussed earlier. Two finite state machines are utilised where one machine describes the storage behaviour and the other the grid support behaviour. The grid support state machine shown in Figure 6.5 supplies energy when the generation devices are not able to meet the load demand. The storage state machine shown in Figure 6.6 stores surplus energy by charging up the battery. Before the smart battery enters either state machine the procedure shown in Figure 6.4 is performed to establish the health of the battery which will determine if a connection to the PeCo grid is allowed.

Voltage (V)	Inferred Information
$0 < V_{bat} < V_{bat_{min}}$	Battery faulty or unsafe for use
$V_{bat_{min}} \leq V_{bat} \leq V_{bat_{max}}$	Battery usage allowed
$V_{bat} \geq V_{bat_{max}}$	Battery overcharging

Table 6.2: Lead-acid battery terminal voltage inference engine where V_{bat} is the terminal voltage

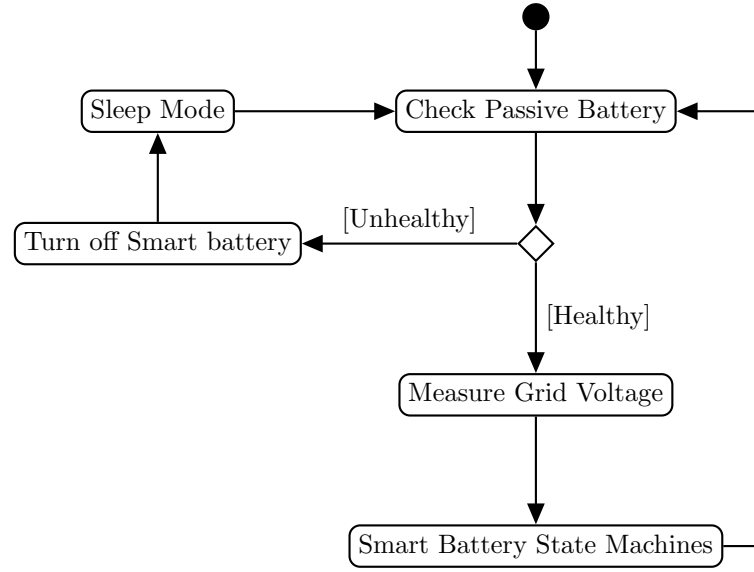


Figure 6.4: Smart battery instruction cycle routine.

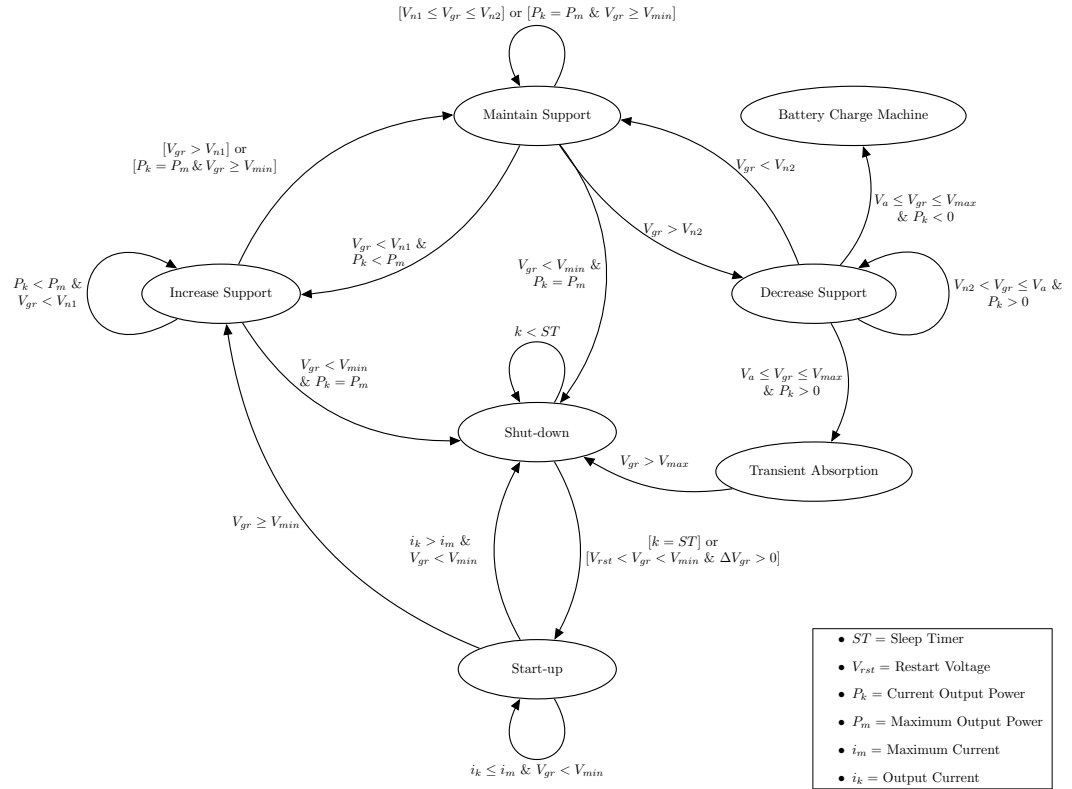


Figure 6.5: Grid support state machine for the smart battery.

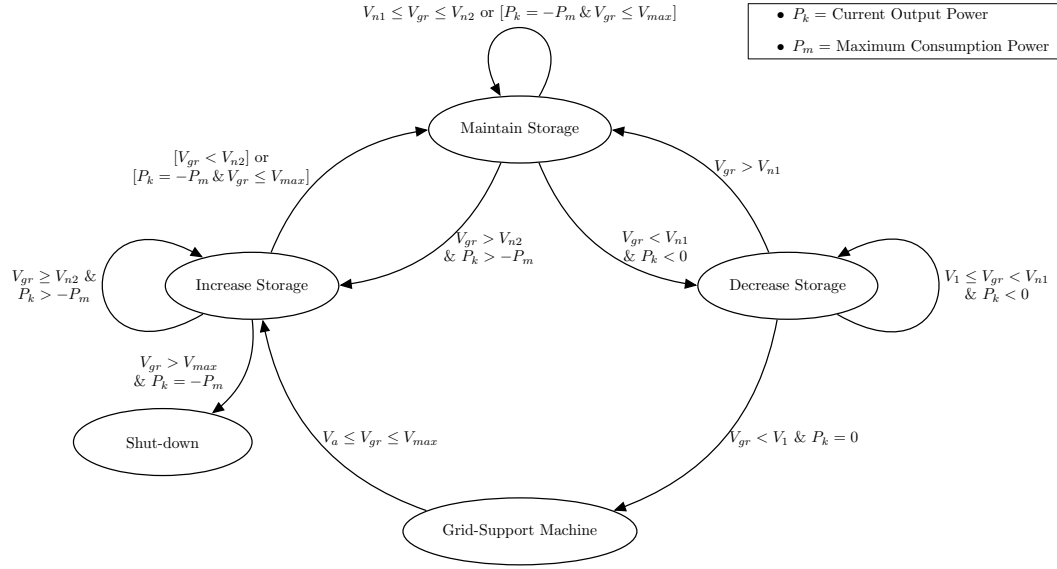


Figure 6.6: Battery charge state machine for the smart battery.

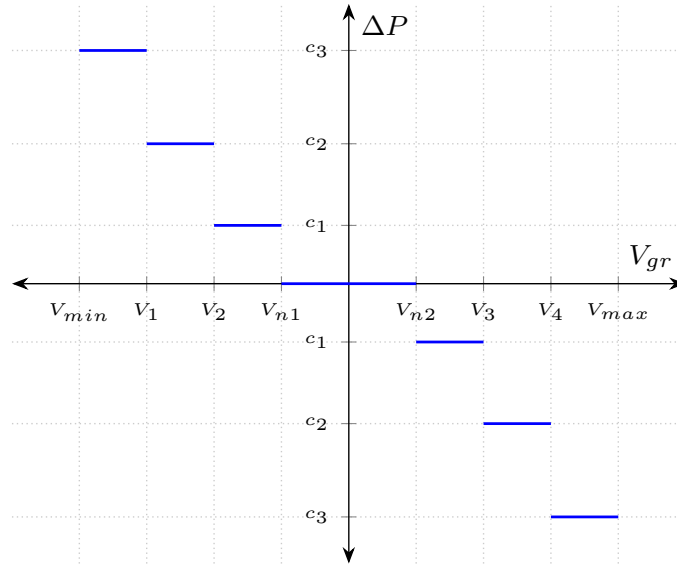
6.4.1 Increase Supplied Power

During the *increase support* state, the smart battery increases its output power using equation (6.1). An increase in power implies that $\Delta P > 0$ which results in the rising of the grid voltage V_{gr} . The increment by which the power is increased varies depending on the current status of the grid voltage. Three discrete increase increments are proposed as depicted in Figure 6.7 where a higher ΔP is used when the grid voltage is closer to the minimum voltage V_{min} . As the grid voltage trajectory approaches V_{n1} , ΔP is decreased as the smart battery infers that the grid health is improving.

$$P_k = P_{k-1} + \Delta P \quad 0 \leq P_k \leq P_{max} \quad (6.1)$$

6.4.2 Decrease Support

The *decrease support* state is the inverse operation of the increase state. In this state $\Delta P < 0$ in equation (6.1) resulting in a reduction of the grid voltage V_{gr} . This state occurs when the device's power output is higher than required which causes the grid voltage to rise. The three discrete decrements described in Figure 6.7 indicate that the power decrement is largest when the grid voltage is nearing V_{max} . Similar to the increase state, as the voltage trajectory approaches V_{n2} the magnitude of the decrement decreases.

Figure 6.7: ΔP for increase and decrease support/storage states

6.4.3 Increase Storage

The *increase storage* state increases the energy absorption from the grid. This state stabilises the grid by absorbing the surplus energy on the grid and storing it in the passive lead acid battery. The absorption rate is controlled by the power consumption of the smart battery as shown in equation (6.2). Similar to the support states, discrete ΔP levels are used which depend on the grid voltage as shown in Figure (6.1). As the power transferred to the battery increases $\Delta P < 0$. The increase in battery charge current results in the grid voltage decreasing. When the voltage trajectory approaches V_{n2} the change in power consumption decreases.

$$P_k = P_{k-1} + \Delta P \quad - P_m \leq P_k \leq 0 \quad (6.2)$$

6.4.4 Decrease Storage

The *decrease storage* mode is used to reduce the power consumption of the battery when the generation devices are not providing as much power as they previously were. In this state the consumption rate is reduced as the grid V_{gr} tends towards V_{min} . The discrete changes in power are shown in Figure 6.7 which indicates that the device reduces the magnitude of ΔP as the grid voltage approaches V_{n1} . During this state $\Delta P > 0$ as the battery charge current is being reduced.

6.4.5 Maintain Support and Storage

These states are common to both modes of operation and occur when the above-mentioned states are able to force the grid voltage to the nominal region, indicating a healthy grid. During this state $\Delta P = 0$ and the smart battery continues to maintain a constant power output. As the bounds V_{n1} & V_{n2} tend to each other, the regulation of the grid becomes tighter. This tighter regulation results in an oscillation about nominal voltage due to the manner in which the previously discussed states approach the nominal voltage. By relaxing the nominal bounds a nominal region is formed instead which results in a less tightly regulated grid. However, the grid voltage will no longer oscillate about a single point but will lie in the nominal region.

6.4.6 Transient Absorption

The transient absorption state is designed to reduce the rise in grid voltage that occurs when the grid structure changes. This change occurs when devices are plugged in to or out of the grid. This mode targets the scenario where the smart battery is supporting the grid and the load profile changes. If there is a transition between loading to no loading of the smart battery, the output capacitors charge up as the device's output power level has not changed. The charging could result in $V_{gr} > V_{max}$ as the new power output level is discretely stepped through. With no load to dissipate the power, the device is forced to shut-down. A false shut-down is prevented by using the transient absorption logic developed in Figure 6.8 which results in the charge on the bus capacitor being discharged into the lead-acid battery. If discharging fails it implies there is an overvoltage condition and shut-down is necessary.

6.4.7 Shut-down

The shut-down state is used to protect the grid and lead-acid battery during a fault event. In the shut-down state, the device's output power is zero. If all devices on the grid turn off, no power is dissipated and the overall grid is protected. The conditions for an overvoltage fault occurs when the $V_{gr} > V_{max}$ and an under-voltage fault occurs when $V_{gr} < V_{min}$. Under voltage is associated with grid overloading or short circuit faults.

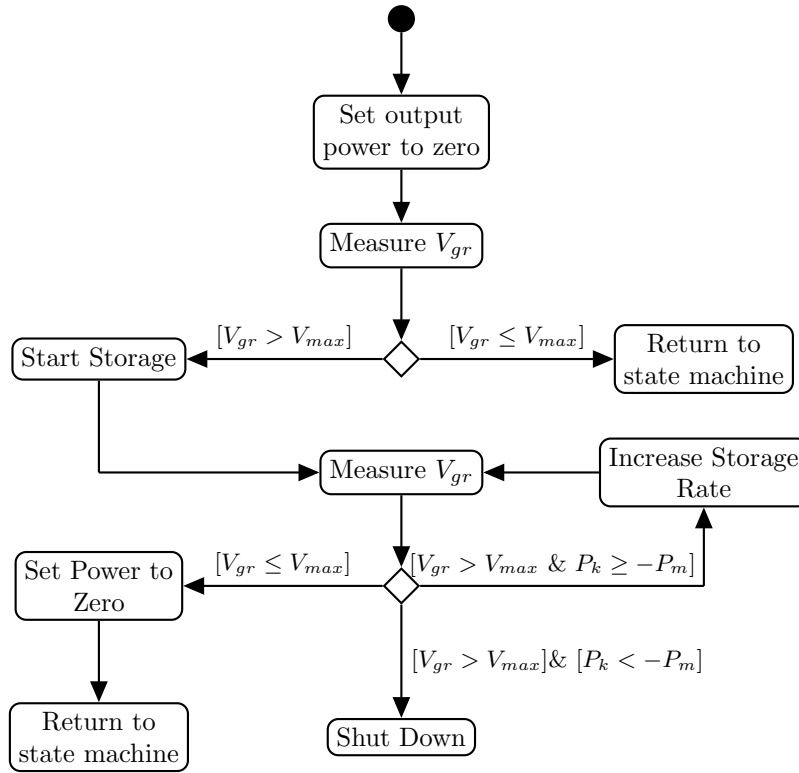


Figure 6.8: Transient absorption logic.

6.4.8 Restart

After a shut-down event, it is necessary to restart all devices using a soft start as mentioned earlier. The rising grid voltage gives additional devices on the grid an opportunity to synchronise their startups using the logic shown in Figure 6.9. This synchronisation allows for black starting of loads larger than the power capability of a single device. If a restart fails, that is the device is unable to raise $V_{gr} > V_{min}$ even though maximum current is injected into the grid, the device shuts down and goes into a sleep mode. In this mode, the device monitors the grid voltage observing if other devices are attempting to restart the grid which is inferred using Table 6.1. The sleep mode will only last for a finite amount of time before attempting a restart.

6.5 Battery Management

The battery management is carried out using the algorithm in Figure 6.10. The management algorithm uses the SOC and terminal voltages of the battery to manage it. The SOC is computed using the Coulomb counting technique in equation (6.3) which computes the SOC change when the battery is being loaded. However, this

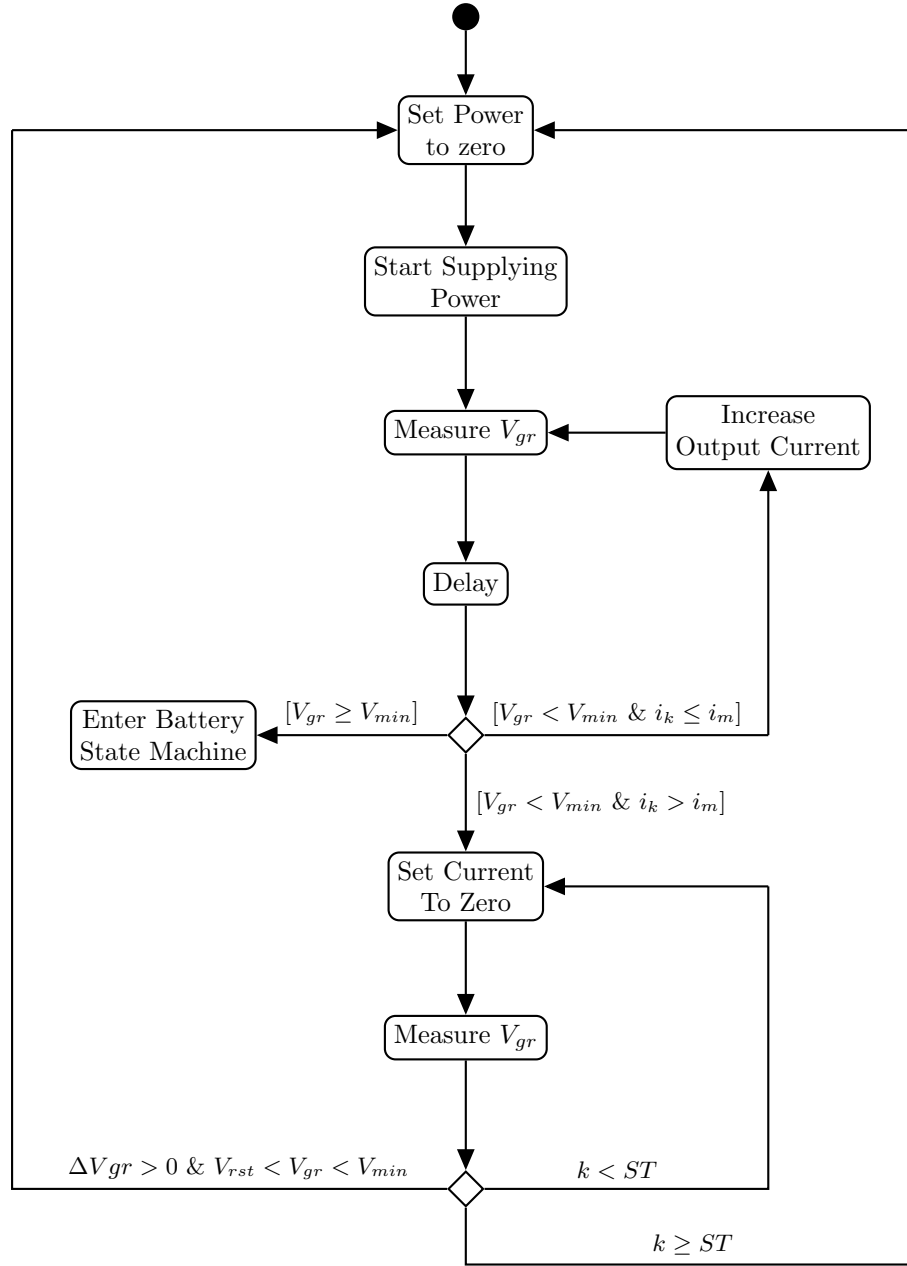


Figure 6.9: Start up procedure for the smart battery on a PeCo grid.

method is an integral based method which results in the wind-up of the error from the measurements. To overcome this the battery terminal voltage is used to reset the SOC. This is accomplished by using the linear OCV and SOC relationship discussed in Chapter 4. As shown in Appendix H the true open circuit voltage of the battery cannot be established instantaneously when the load is disconnected. Due to the RC nature, a waiting period is utilised before resetting the SOC counter. The SOC computation happens at a much slower rate in comparison to the grid stabilisation

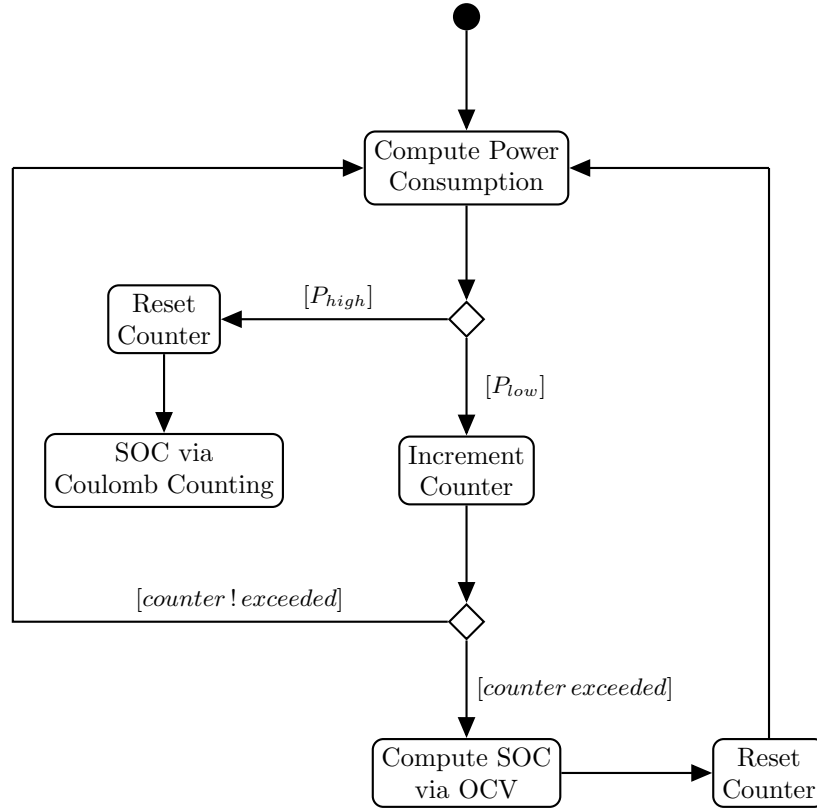


Figure 6.10: SOC computation and reset procedure used for battery management.

routine and is performed once every second.

$$SOC = \eta_b \Delta t \frac{i_k + i_{k-1}}{2C} + SOC_{k-1} \quad (6.3)$$

where η_b is the battery charge/discharge efficiency, i_k [A] is present current measurement, i_{k-1} [A] is the previous current measurement, C [Ah] is the total battery capacity, Δt is the time between the present and previous measurements and SOC_{k-1} is the previous state of charge value.

In addition to the SOC, the terminal voltage is used for battery protection. The smart battery is only allowed to participate in the PeCo grid if the voltage of the lead-acid battery terminals are between $V_{bat_{min}}$ & $V_{bat_{max}}$. The charge curve for the lead-acid battery is shown in Figure 6.11 under constant generation. Due to the varying nature of renewable generation, the battery charge current is upper bounded by i_{max} during the constant current phase of the charging but can be any current in the shaded region. Similarly the constant voltage phase of charging bounds the charge voltage to V_{max} . As generation varies below the maximum bounds the time t_1 shifts to the right as the battery takes longer to charge.

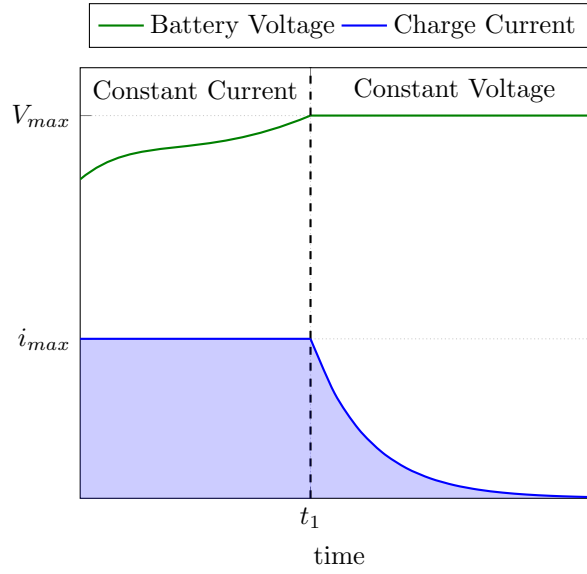
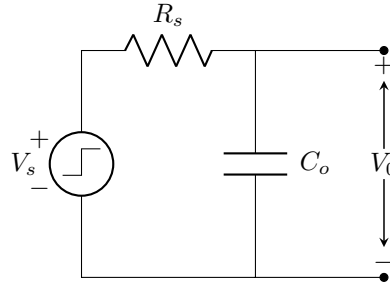


Figure 6.11: Lead-acid battery charge curve.

Figure 6.12: Model of smart battery when changing ΔP .

6.6 Output Capacitance

The model of the smart battery when changing its output power is seen in Figure 6.12 where R_s is the internal resistance of the smart battery and C_o is the output capacitance of the battery. When the output power changes a step voltage is applied to the RC network. As the entire control algorithm is based upon the steady state value on the output capacitor it is important that the control algorithm does not change its power level while the capacitor is approaching its steady state value. If the battery makes a change before the capacitor reaches its steady-state value, the smart battery will not be able to set the power output to a level that forces the voltage trajectory into the healthy grid region. This can be resolved by ensuring the power output is changed once RC network reaches steady-state.

6.7 Conclusion

The control action required to achieve the required functionality has been developed in this chapter. Using these control algorithms the smart battery has the ability to interface with the PeCo grid. The algorithms give the smart battery functionality such as fault protection, black starting and grid stabilisation. Including interfacing to the PeCo grid the smart device performs battery management of the lead-acid battery. The management of the battery utilises Coulomb counting and the open circuit voltage of the lead-acid battery to establish the SOC of the device. The next chapter experimentally validates the control algorithms of the smart battery.

Chapter 7

Smart Battery Performance

This chapter evaluates the performance of the smart battery to establish the effectiveness and identify its shortcomings of the algorithm developed in Chapter 6. The performance of the battery is evaluated using the test grid developed in Appendix G. The test bed allows for the grid scenarios discussed in Section 6.1 to be replicated in order to observe the behaviour of the smart battery.

7.1 No Generation on the Grid

During this scenario, there are no generation elements on the grid and the smart device is required to regulate the grid voltage (V_{gr}) as the load profile varies. The setup shown in Figure 7.1 is used to recreate this scenario. The variable resistor R_L is varied using the profile shown in Figure 7.2 and the respective behaviour exhibited by the smart battery is depicted in Figure 7.3. The profile was selected due to its non linearity. The figure demonstrates the ability of the smart battery to increase and decrease its power output to ensure that the grid voltage remains regulated around 12 V. At 31 s the resistance changes from minimum resistance to the maximum resistance resulting in a transient on the grid voltage.

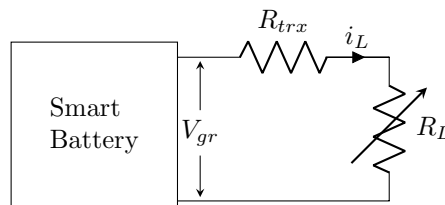


Figure 7.1: Test set-up used for the varying load with no generation where $R_{trx} = 8\text{ m}\Omega$ and $2.5\text{ }\Omega \leq R_L \leq 17.5\text{ }\Omega$.

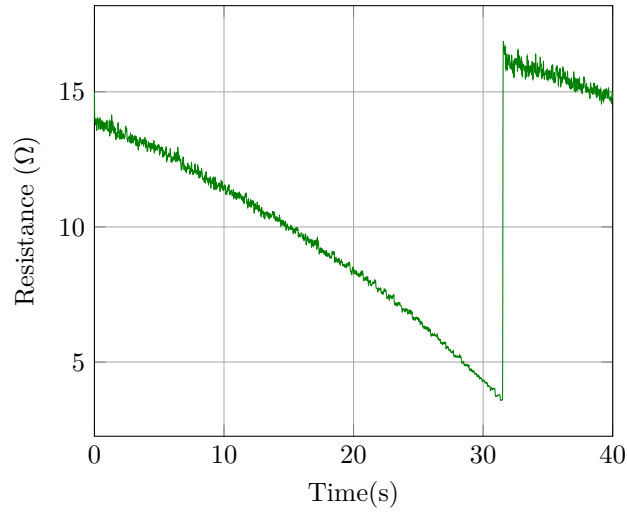


Figure 7.2: Variable resistor profile used for the varying load test.

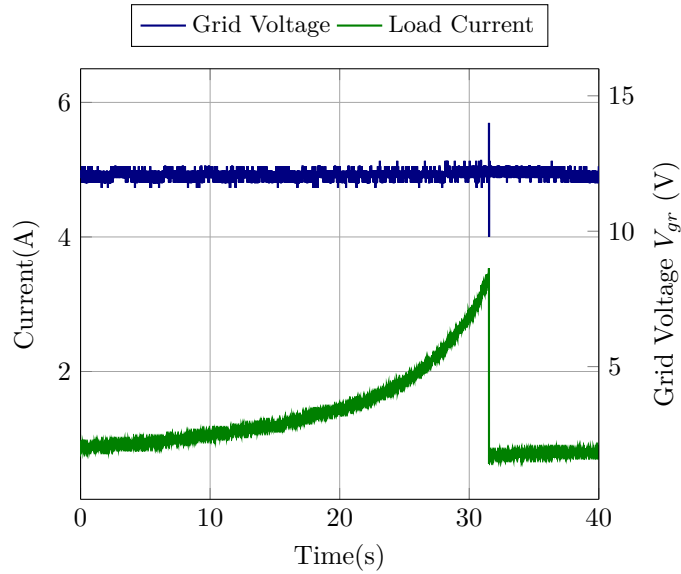


Figure 7.3: Voltage and current response when varying the load with no generation.

This transient behaviour is further investigated using the set-up shown in Figure 7.4. A step load test is conducted by opening switch S_1 resulting in the waveforms shown in Figure 7.5 which show the behaviour that occurs when the load or the smart battery is disconnected from the grid. As there is no prior knowledge of the disconnect event, the device continues to maintain its output power which results in an increase of the voltage V_{gr} . This increase is detected by the device and it attempts to reduce the stored energy on the capacitors by transferring it to the battery which causes the reduction of the grid voltage. Once the voltage is within the bounds the smart battery re-adjusts its output power. The power re-adjustment causes an oscillatory behaviour as the battery attempts to move the voltage trajectory to the

stable region.

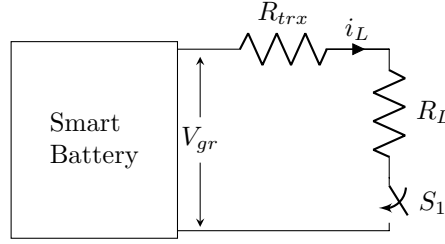


Figure 7.4: Test set-up used for the step load experiment where $R_{trx} = 96\text{ m}\Omega$ and $R_L = 0.96\text{ }\Omega$.

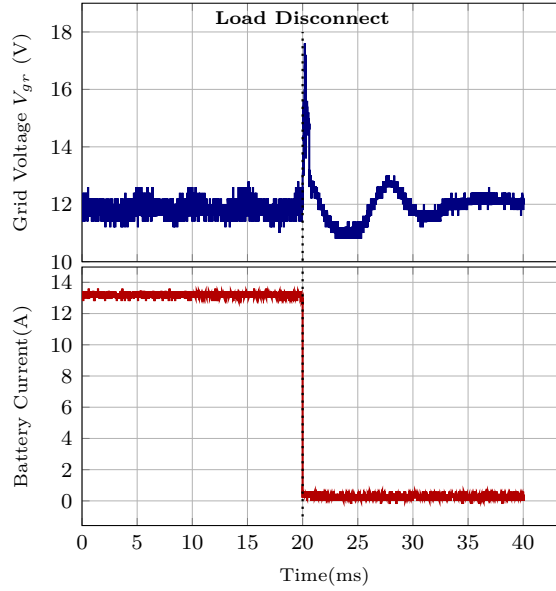


Figure 7.5: Grid voltage and load current when disconnecting a $0.96\text{ }\Omega$ load.

The load connect test emulates the behaviour when a load is connected to the smart battery. This test shows that at the point of connection there is current flow from the output capacitors of the smart battery to the load which results in a collapsing of the voltage V_{gr} . This falling voltage is detected and the battery increases its power output until the grid voltage reaches the operational region. The grid voltage is stabilised at V_{gr} which is measured at the output of the smart battery as illustrated in Figure 7.4.

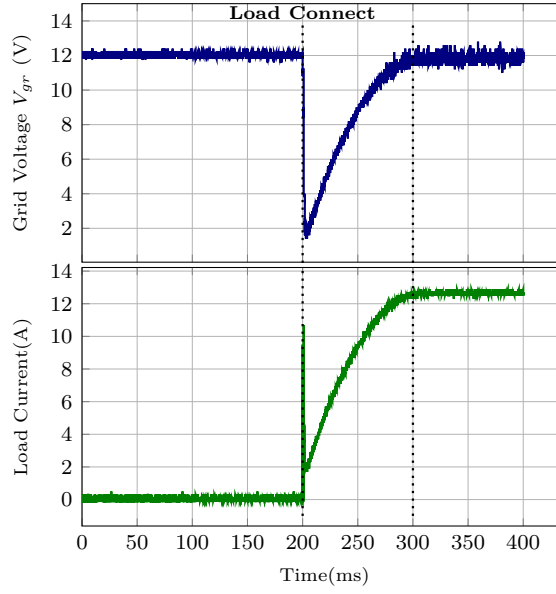


Figure 7.6: Grid voltage and load current when connecting a $0.96\ \Omega$ load

7.2 Lightly Loaded Grid

These tests are used to evaluate the battery behaviour when there is no loading on the grid and are carried out using the set-up shown in Figure 7.7. The generation emulator is implemented using a bench power supply with the voltage and current transfer function shown in Figure 7.8. The output voltage is regulated at a voltage of V_s until it reaches the current limit i_s . The current limit point i_s is varied to emulate a variable generation profile as shown in Figure 7.9.

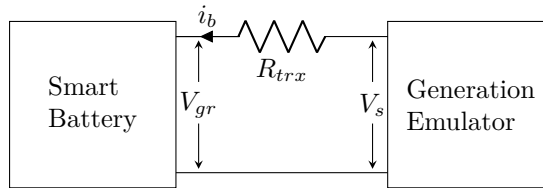


Figure 7.7: Test set-up when varying generation with no loading where $R_{trx} = 64\ m\Omega$.

The battery response to the variable generation profile is shown in Figure 7.10. During the time interval $0 \leq t \leq t_0$ there is no generation current and the battery supports the grid in order to keep the grid voltage regulated. Between $t_1 \leq t \leq t_2$, the generation devices produce energy causing an increase in the grid voltage and this is detected by the smart battery which begins storing the energy. At t_2 the generation energy begins to reduce and the smart battery decreases its charge current accordingly to ensure the grid voltage is stable. This proves that the smart battery

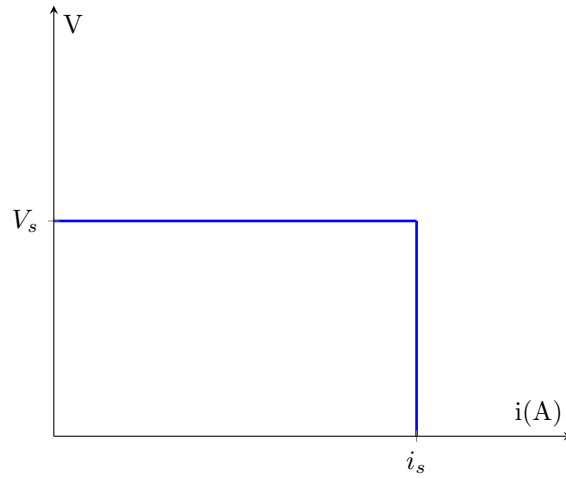


Figure 7.8: V-I curve for generation emulator implemented using a current limited DC bench supply.

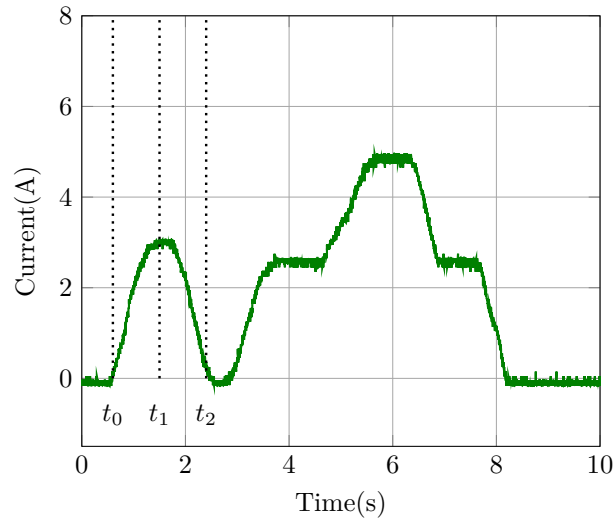


Figure 7.9: Varying generation profile.

absorbs all the available solar energy while ensuring grid stability.

To observe the behaviour when the battery switches from support to storage mode, the test depicted shown in Figure 7.11 is performed. The switch S_1 is connected and the response from this event is shown in Figure 7.12. When the generation device is connected to the grid the smart battery is supplying power which causes the grid voltage to rise sharply and the battery to switch into storage mode. The battery increases its storage power until the grid storage stabilises and maximum power is consumed.

Figure 7.13 shows the behaviour when the battery is disconnected while storing

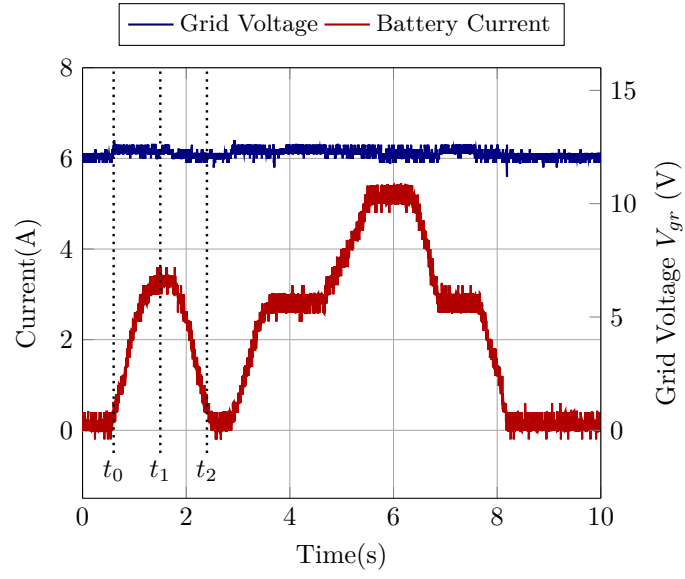


Figure 7.10: Performance curves when varying generation with no passive loading.

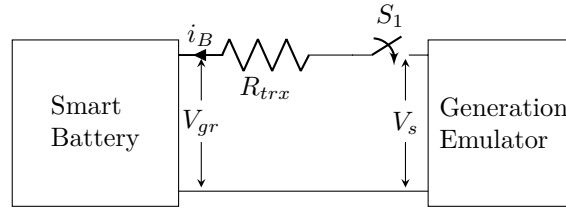


Figure 7.11: Test set-up for step response when connecting a generation element with no passive loads on the grid. $R_{trx} = 64\text{ m}\Omega$.

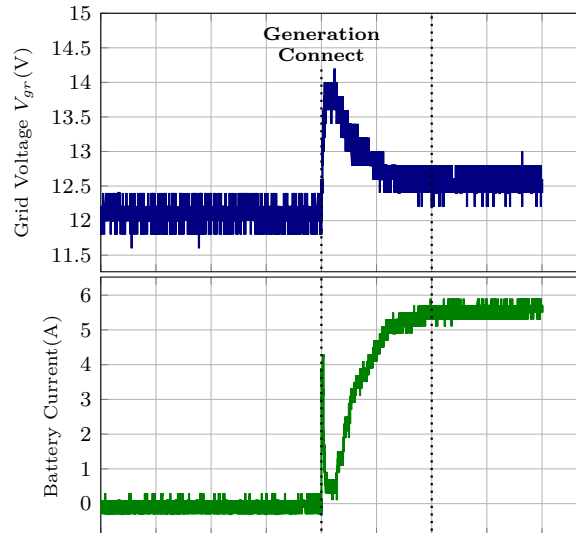


Figure 7.12: Smart battery response when connecting a generation device.

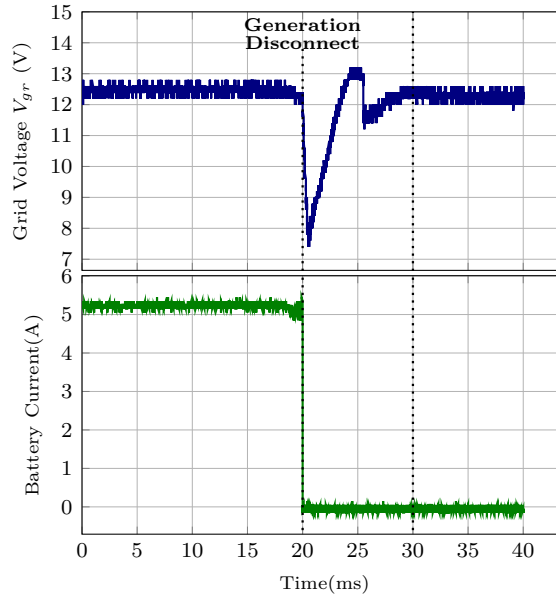


Figure 7.13: Smart battery response when disconnecting a generation device.

energy. This response is extracted by opening the switch S_1 while the battery is charging. At the disconnect event, the smart battery discharges the energy stored on its output capacitors into the battery which causes the grid voltage V_{gr} to fall. The control algorithm corrects this and switches to grid support mode to ensure the V_{gr} voltage is stabilised.

7.3 Fully Functional Grid

This examines the behaviour of the smart battery when there are generation and load elements on the grid as shown in Figure 7.14.

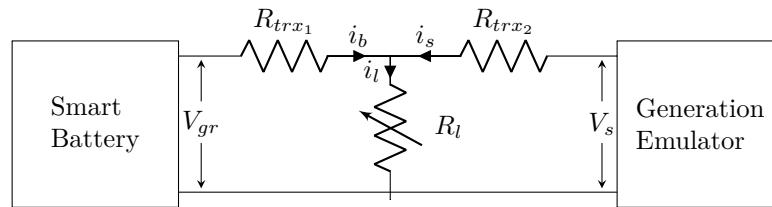


Figure 7.14: Test set-up for a fully functional grid with variable generation and load where $R_{trx1} = R_{trx2} = 48\text{ m}\Omega$.

The first test is conducted by keeping the load resistance constant and varying the generation. Between the time interval $0 \leq t \leq t_0$, there is additional energy after the

load is supplied and the battery stores this. At t_1 , the generation current meets the load requirement and no energy is stored in the battery. During the time interval between $t_1 < t \leq t_2$ the generated energy is decreasing and grid support is provided by the smart battery as it increases its output current in order to stabilise the grid voltage. This support action is continued between $t_2 \leq t \leq t_3$ where the generation current is zero and the grid is completely stabilised by the smart battery. During the next time interval, generation energy is available and the smart battery reduces its supplied energy.

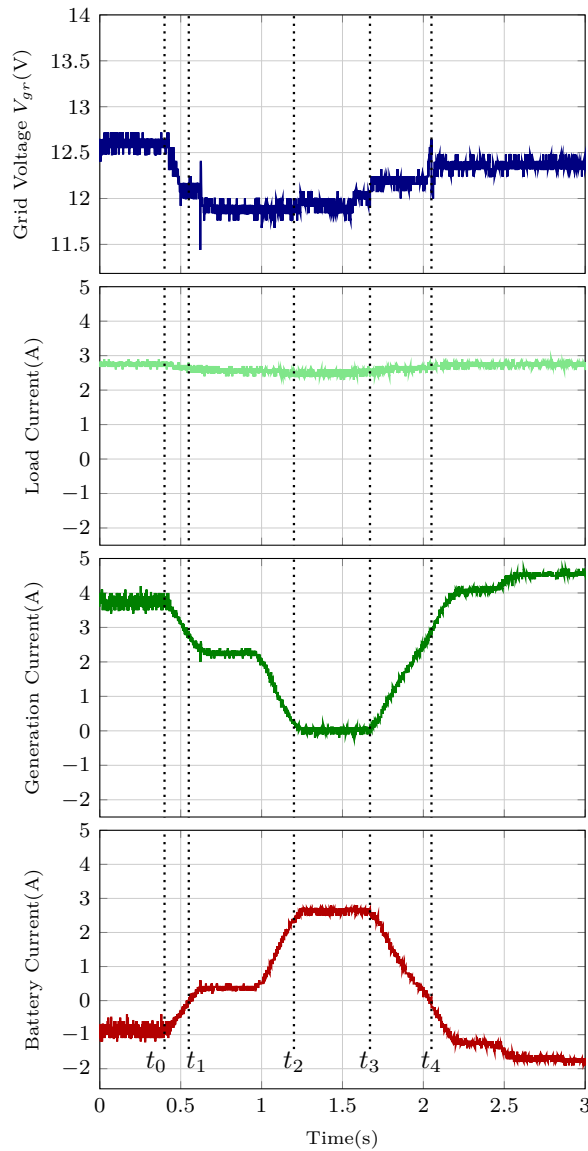


Figure 7.15: Smart battery response when varying generation for a 4.5Ω fixed load for the in Figure 7.14.

This test comprehensively shows how the smart battery symbiotically interacts with

the generation elements. A key demonstration from this test is the ability of the device to allow for generation to take priority in supplying loads and providing support only when the smart generation cannot meet the load demand. Similar to the fixed load test the smart battery demonstrates the same characteristics when the load and generation are varied simultaneously as shown in Figure 7.15. The noise on the grid voltage is a result of the variable resistor controller described in Appendix G which provides a digital load emulator. The digital resistor was selected over a conventional resistor as a time varying non-linear profile could be replicated in a repeatable manner.

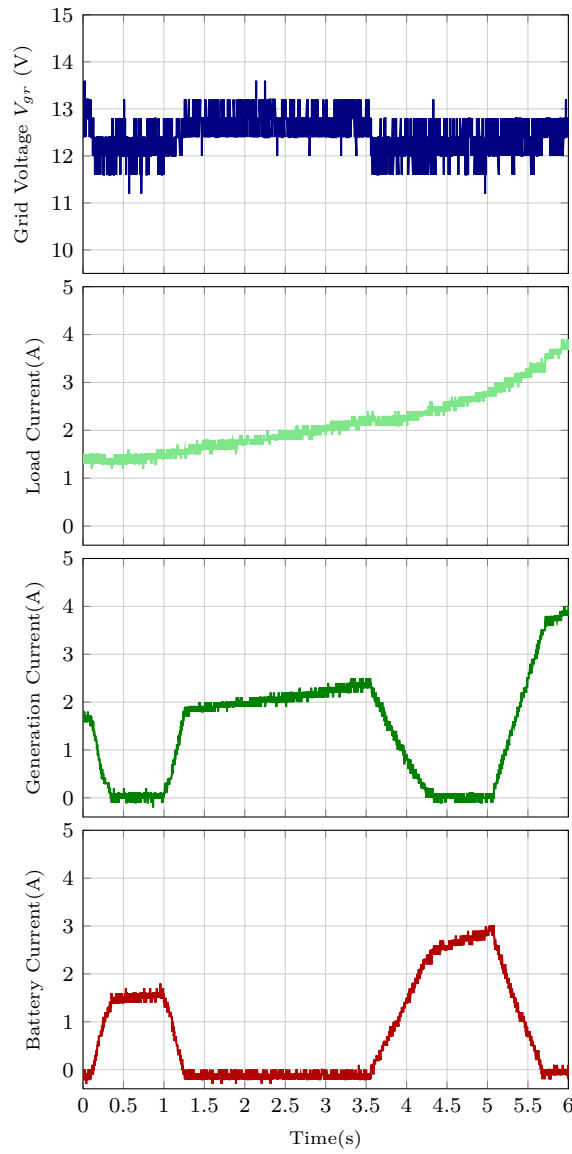


Figure 7.16: Smart battery response when varying both the generation and load using the set-up in Figure 7.14.

7.4 Scaling

The test shows the scalability of the smart battery to integrate into an existing network seamlessly by plugging in a second device. The set-up in Figure 7.17 shows two smart battery devices connected to the grid with no generation devices present. The resultant waveforms from the experiment are shown in Figure 7.18. Initially battery one is sustaining a 150 W load which is close to the maximum power capability of a single smart battery. At time t_0 switch S_2 is closed, increasing the total load requirement to 300 W. The close up of the behaviour from the various devices at time t_0 is shown in Figure 7.19. Examining the behaviour at t_0 , it is observed that the grid voltage can only be raised to 8 V when the device is at its maximum current output. This is below V_{min} hence the device shuts down. A restart attempt occurs at t_1 as shown in Figure 7.20 but fails due to there being only one battery operational at this time. At time t_2 switch S_1 is closed and the system restarts as shown in Figure 7.21. The output capacitors of battery two are discharged at the time of closing switch S_1 as the voltage $V_{gr} = 0$ V while the output of the second battery is 12 V. Battery one detects a ΔV_{gr} and starts up. Since the total power capability of both devices is slightly over 300 W the load demand can be met and the grid voltage $V_{gr} \approx 12$ V. Although both devices are sustaining the grid they do not share the current equally as they both see different voltages at their respective connection point.

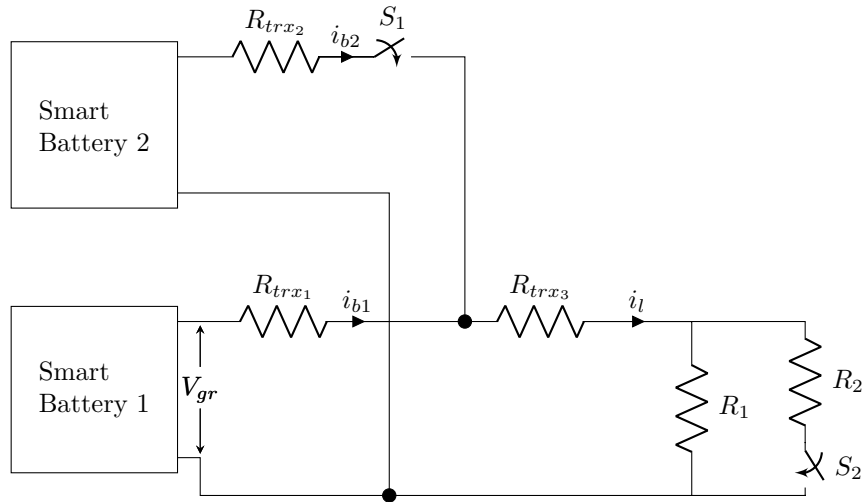


Figure 7.17: Test set-up used for scalability test where $R_{trx1} = 16\text{ m}\Omega$, $R_{trx2} = 32\text{ m}\Omega$, $R_{trx3} = 96\text{ m}\Omega$, $R_1 = 0.83\text{ }\Omega$ and $R_2 = 0.95\text{ }\Omega$

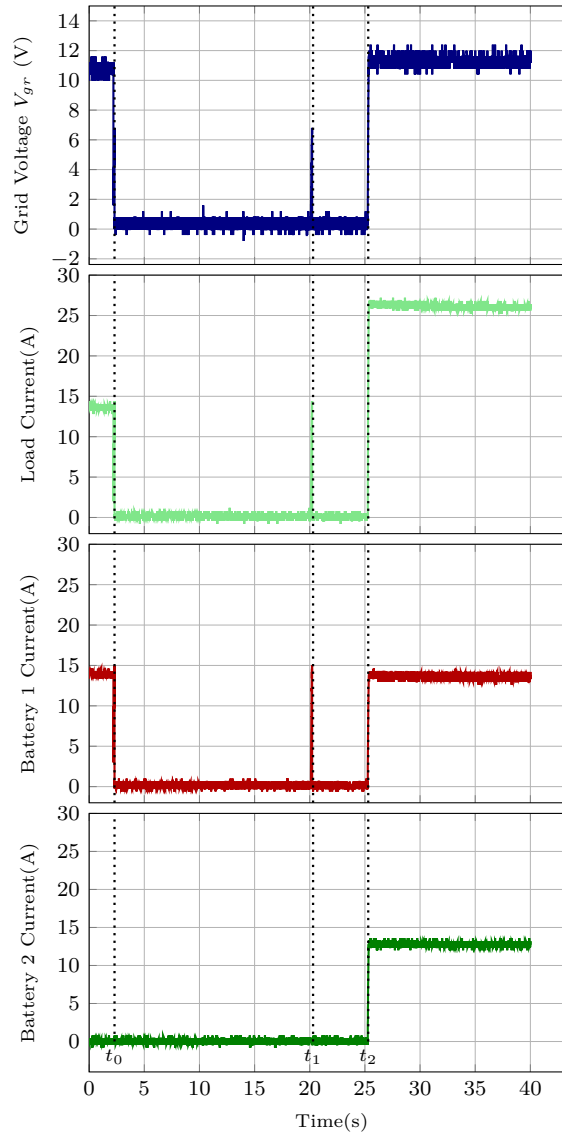


Figure 7.18: Performance waveforms of the two batteries when scaling system from 150 W to approximately 300 W.

7.5 Short circuit protection

The short circuit protection is conducted using the test set-up in Figure 7.22. During this test, two smart batteries supply 300 W load and a short circuit is applied. Figure 7.23 shows the behaviour when the fault condition occurs. Three key segments of this event are examined to understand the behaviour during the fault event. At time t_0 switch S_2 is closed which places a short circuit on the system. The behaviour at time t_0 captured in Figure 7.24 shows that when the grid is shorted, the voltage at V_{gr} collapses. This collapse results in both devices attempting to restart the grid, however, the voltage cannot be raised due to the short condition. The failure to

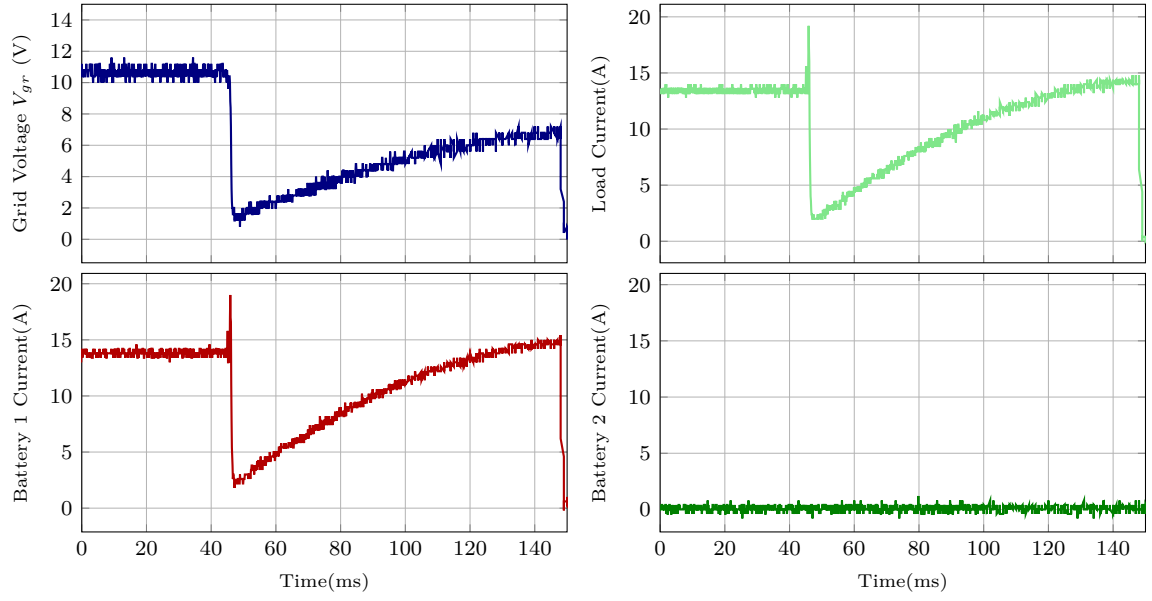


Figure 7.19: Performance when a 300 W device is connected.

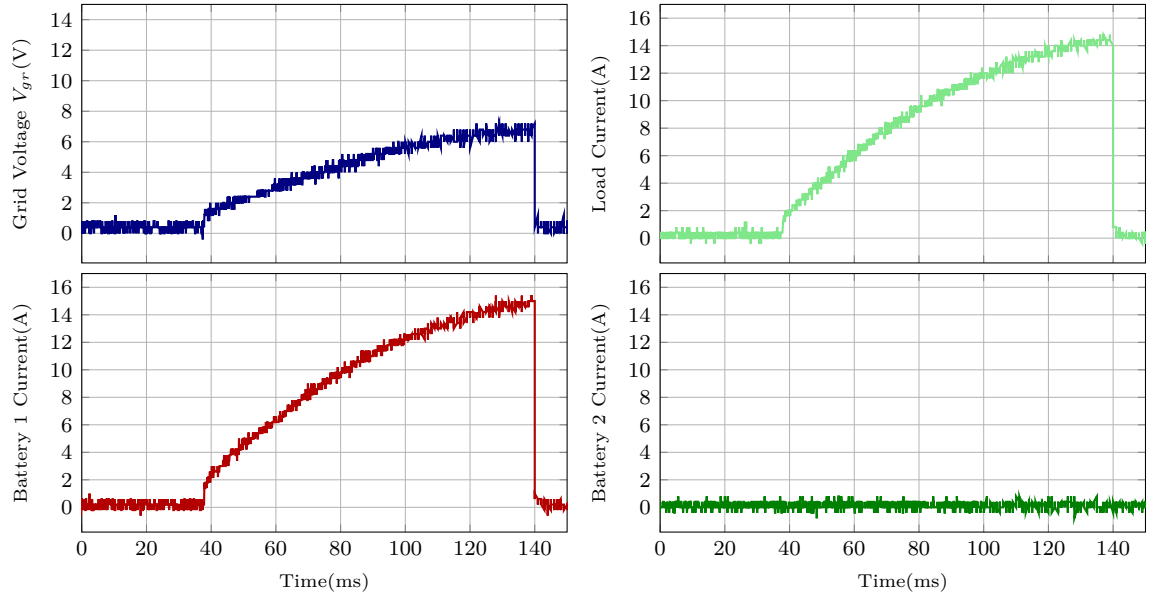


Figure 7.20: Failed restart where one device is trying to start up a 300 W load.

raise the grid voltage forces the device into a sleep mode which expires after a finite duration. After the device exits the sleep mode, it attempts to restart the grid during $t_1 \leq t \leq t_2$. The restart attempts are that of individual devices as there is no prior communication as to when each device will attempt a restart as the events are not synchronised. The restart attempt of battery one is shown in Figure 7.25 which illustrates how the smart battery ramps its output current but is unable to raise the grid voltage V_{gr} . This failure to raise the grid voltage forces the device to return to the sleep mode. At time t_2 , the switch S_2 is opened and the fault is removed. During

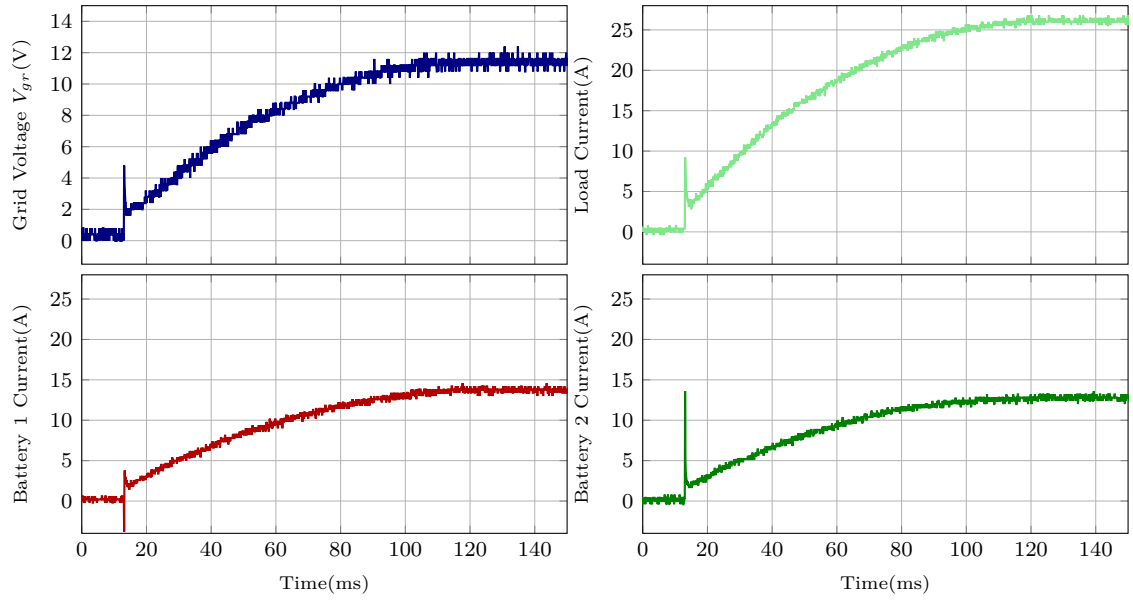


Figure 7.21: Grid start up when a second smart battery is inserted.

the second periodic attempt at a restart by battery one seen in Figure 7.26, it can be observed that device one is able to raise the grid voltage above the V_{rst} voltage level. Device two notices the change in the grid voltage and the raising above V_{rst} which brings it into restart mode. This restart happens 20 ms after device one initialises a restart. The smart batteries are able to synchronise their restarts of both devices and supply a 300 W. This load is greater than the power capability of a single device. This experiment demonstrates the self-healing capability of the smart battery and its ability to black start the PeCo grid.

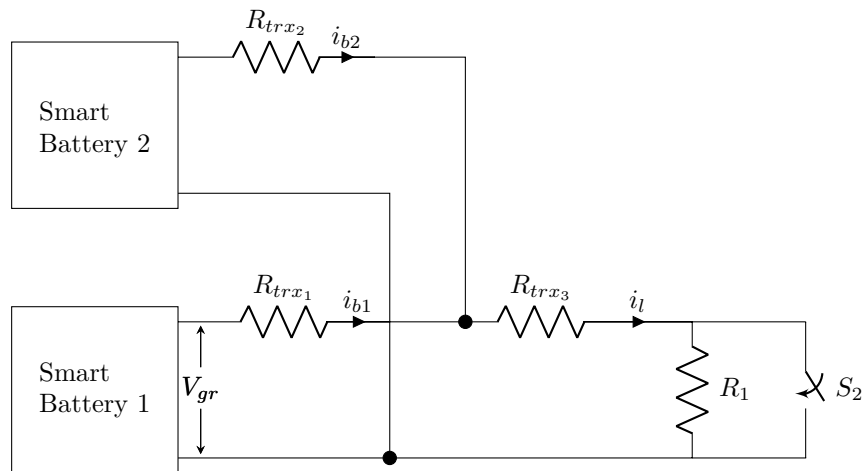


Figure 7.22: Test set-up used for fault event test when a short circuit event occurs where $R_{trx1} = 16 \text{ m}\Omega$, $R_{trx2} = 32 \text{ m}\Omega$, $R_{trx3} = 0.96 \text{ m}\Omega$ and $R_1 = 0.45 \Omega$.

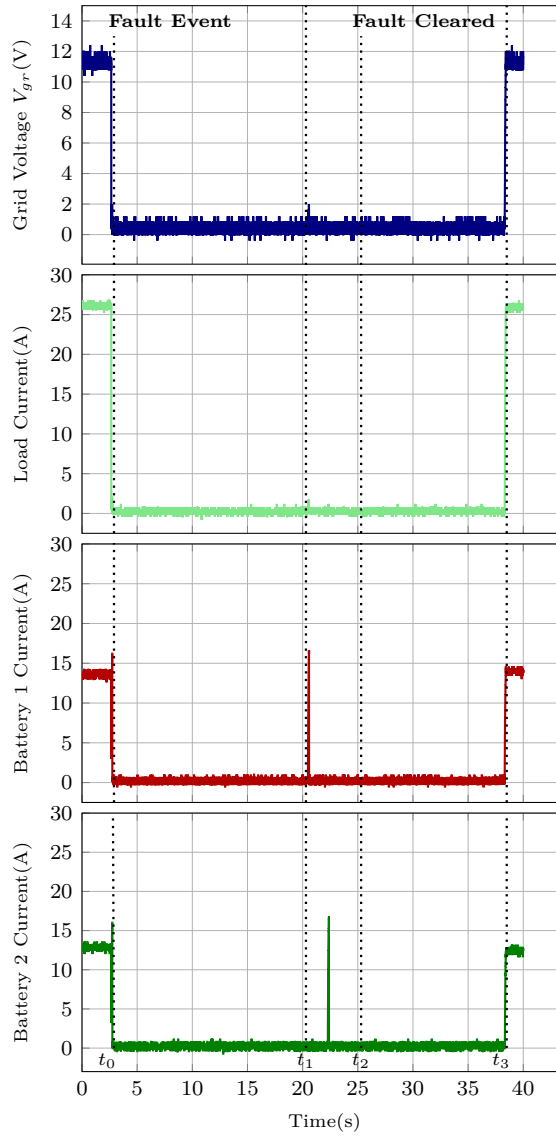


Figure 7.23: System behaviour during a short circuit fault.

7.6 Battery Charging

The battery charging is validated using the generation test shown in Figure 7.7. A fully charged smart battery is interfaced to a generation emulator capable of providing $i_s = 6$ A of charge current. Figure 7.27 shows the behaviour when the described scenario occurs. Even though there is additional energy available, the smart device only absorbs sufficient energy to keep the terminal of the passive lead-acid battery at a float voltage of 14 V. This ensures that the battery is not overcharged. The correct behaviour of the smart battery charging during the constant current mode of charging is proven by the tests conducted in Section 7.2.

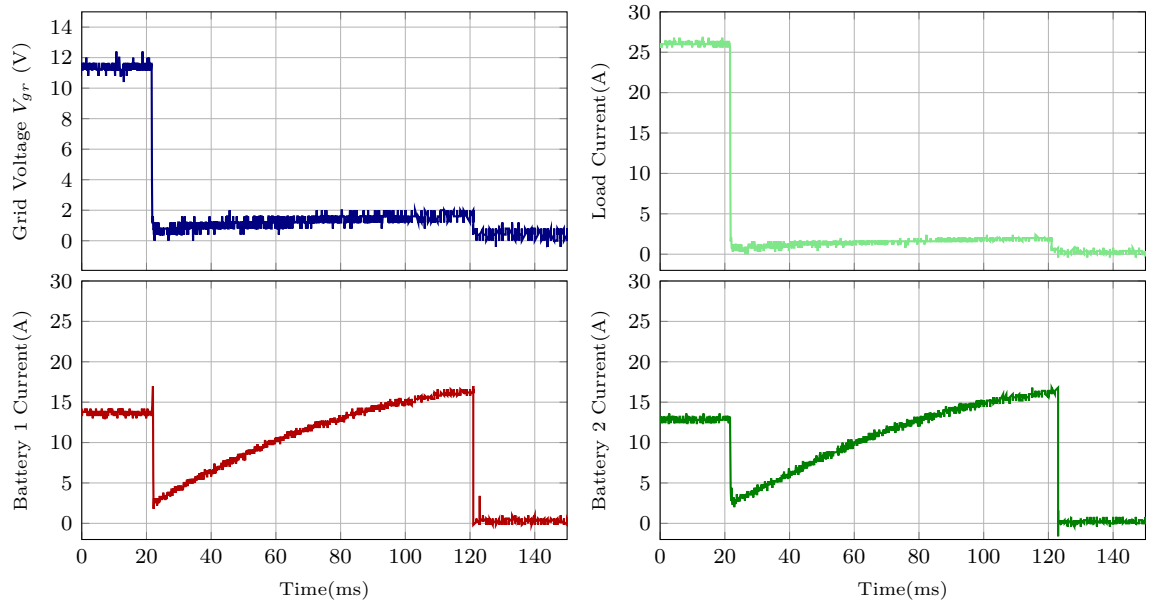


Figure 7.24: Zoomed in view of t_0 when the short circuit fault event occurs.

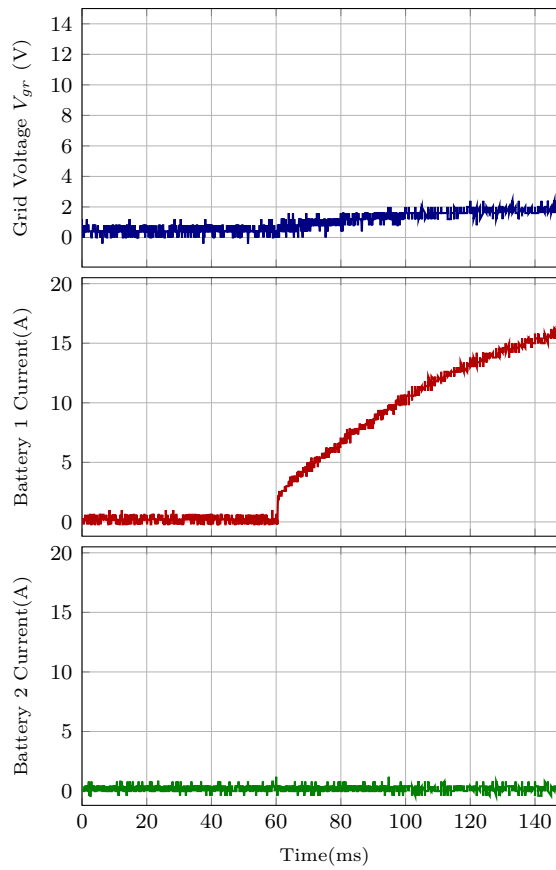


Figure 7.25: Restart attempt at t_1 during the short circuit fault event.

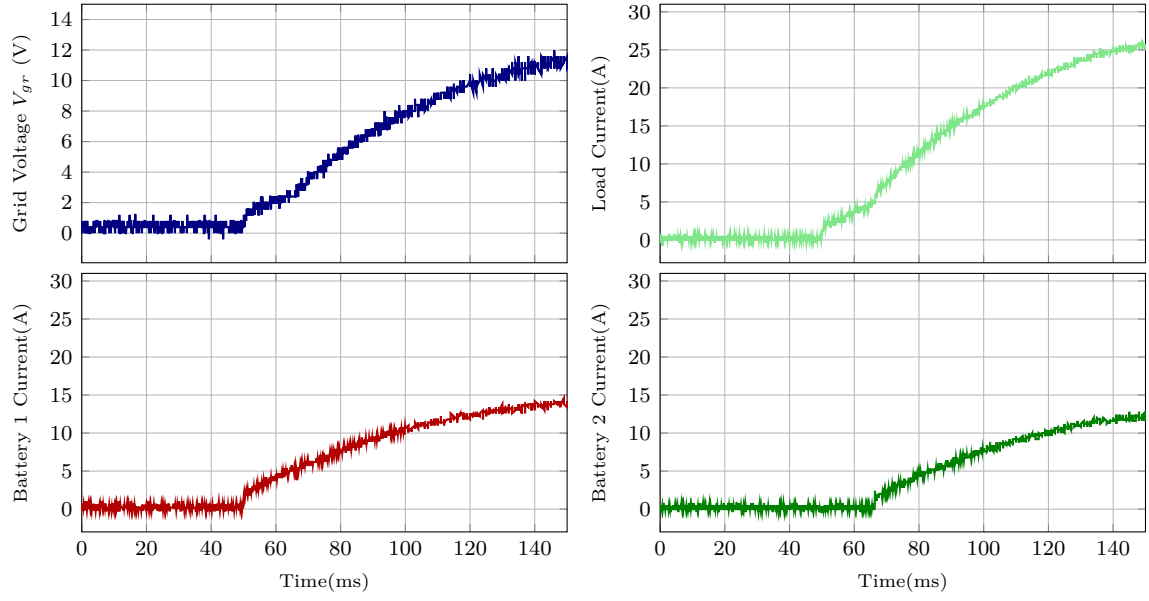


Figure 7.26: Successful restart after short circuit event has cleared at t_2 .

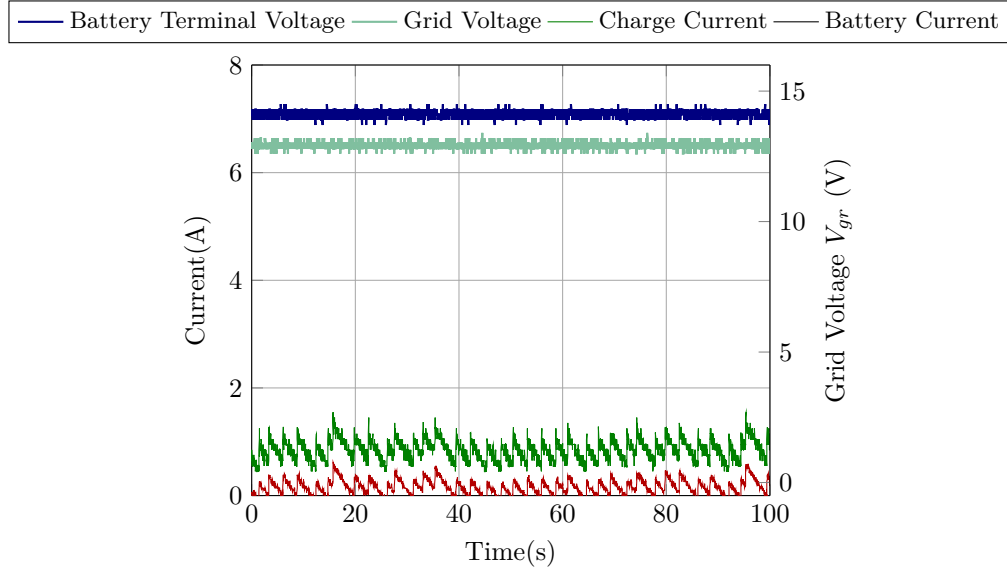


Figure 7.27: Battery end of charge waveforms with no loading and only generation present.

7.7 Conclusion

This section validates the performance of the smart battery which allows for storage to be implemented on an autonomous DC grid. From the tests, the device can seamlessly switch between charge and discharge mode to stabilise the grid voltage V_{gr} . In addition to stabilising the grid, the storage solution is scalable and is completely plug and play. The smart battery can also protect against faults such as overloading

or a short circuit. The battery self-heals when the fault is removed as it is able to automatically restart the grid. All of these features are achieved by monitoring the grid voltage. This method of controlling the device does come at a price as the current is not shared equally between devices and the grid voltage is not tightly regulated. This can be seen by the voltage perturbations occurring during the connect and disconnect of both generation and storage. However, the grid is able to recover from these perturbations and stabilise.

Chapter 8

Conclusion

This work focused on the development of a smart battery in order to add storage to an autonomous 12 V DC grid. The developed smart battery has the ability to store surplus energy and support the grid when energy from generation devices are low. The smart battery consists of a 12 V lead-acid battery connected to a dual active bridge bi-directional DC-DC converter. The DC-DC converter acts as an interface mechanism which modulates the power flow to achieve the required functionality. The following list summarises the work done in each chapter and the main conclusions from the conducted investigations and experimentation.

- Chapter 3 introduces an autonomous 12 V low power DC grid named the PeCo grid. This grid has renewable generation but requires a storage solution. This chapter proposes a grid voltage protocol and equivalent DC models for each element. The model for the storage device is a variable DC voltage source with a variable series resistor shown in Figure 3.3. A key conclusion from this Chapter is that the interested dynamics for which the control action is required is the steady state voltages on the grid.
- Chapter 4 evaluates the various models currently developed for the lead-acid battery which is selected as the battery technology due to its maturity and low cost when compared to other technologies. The simple models fail to adequately capture the behaviour of the lead-acid battery which is non-linear as demonstrated by the Thevenin model discussed in Section 4.1.2. Although the battery is nonlinear, there is a linear relationship between the state of charge and the open circuit voltage of the battery. However, this relationship is only observed when the battery has been offline for a duration of time as there is an internal RC behaviour once the battery is unloaded. Due to this RC behaviour, the true open circuit voltage cannot be ascertained immediately.

- The dual active bridge converter is discussed in Chapter 5 which interfaces the lead-acid battery to the PeCo grid. Using a simple phase shift modulation scheme the power flow can be modulated causing the smart battery to behave as a variable voltage source and resistor. This chapter looks at the design of the converter which is centred around the leakage inductance of the magnetic circuit. Using the guidelines laid out, a dual active bridge converter is built and tested. From the testing, it is observed that the ideal model discussed in Section 5.1 is incomplete and a lossy model for the converter is required. The current solutions for a lossy dual active bridge have a high degree of complexity which makes it undesirable for implementation on a microcontroller due to the computational burden. To overcome this, a loss estimator technique is derived in Section 5.2 which can be applied if losses are bound relative to the leakage impedance.
- As mentioned above the dual active bridge and lead-acid battery combination is simply a variable voltage source and series resistor. This model allows for control algorithms discussed in Chapter 6 to be developed. The control algorithms are based on grid voltage and battery voltage inference systems. This inference method allows the smart battery to be modular and scalable without the use of a dedicated communication link to other devices on the grid. The limitation of using this approach on a DC system is the dependency of the control on the voltage drop between devices. The voltage drop is due to the losses of the interconnecting transmission cables. Using these algorithms, the smart battery can store energy when generation is in excess and support the grid when the available generation cannot meet the load demand. The battery also has fault protection and self-healing capabilities which are all achieved using a plug and play philosophy. Including grid stabilisation, the battery also performs battery management. From the developed algorithms it is deduced that the smart battery is agnostic to the passive storage technology as the management and stabilisation logic are not strongly linked.
- The algorithms discussed above are experimentally validated in Chapter 8. These tests prove that the battery is able to meet the functionality set out earlier. However, the regulation of the bus is not tight as the entire control philosophy hinges on perturbations and observations. Even though the grid is not tightly regulated about the 12 V point, the grid is able to settle to the stable operating region. This is validated from the experimental work which demonstrates that once the grid topology has stabilised, that is no devices are plugged in or out of the grid, the smart battery connection point is a stable

DC voltage with minimal oscillation. These tests also demonstrate the black start capabilities of the smart battery.

8.1 Future Work and Outlook

Although a smart battery has been developed which meets the required functionality there remain areas of this work which require future improvements. Due to there being multiple components which make up the smart battery, each aspect is isolated in the list below.

- As mentioned the lead-acid battery was selected due to its low price and modularity. However, the designed control algorithms are agnostic to the selected technology and only require the battery management to be altered. It would be beneficial to use different technologies such as those discussed in Section 2.3 as other storage mechanisms have longer lifespans and offer additional advantages.
- The experimentally designed dual active bridge converter requires further work with specific attention to the design of the magnetic component. The losses in the magnetic component are the result of the experimental prototype deviating from the lossless model. Alternative modulation schemes with lower RMS currents should be evaluated as this would result in improved efficiency. Interleaved dual active bridges can be used in place of a single device to minimise the overall losses. Not only will this approach reduce losses but the required output capacitance will be reduced as well.
- The control algorithms require more focus on the battery management algorithms. This work implemented a basic strategy for the lead-acid battery to be managed. Advanced battery management should be explored as these carry additional benefits. The control algorithms can incorporate the SOC of the battery to make it more responsive and increase the duration for which the battery can sustain the grid. More focus is required to improve the current sharing between devices. Level specific control naturally results in transient behaviour. This can be addressed by the use of fuzzy boundaries which are not discrete in nature.
- More tests needs to be conducted on a fully operational system to monitor the SOC tracking and charge current variation due to the variation of solar

generation. Load variations such as off-the-shelf 12 V equipment should be tested to replicate a more realistic load profile.

References

- [1] M. Bhatia and N. Angelou, “Beyond connections,” 2015.
- [2] S. Sivanagaraju, *Electric Power Transmission and Distribution*. Dorling Kindersley, 2008. [Online]. Available: <https://books.google.co.za/books?id=KpY1hpKKwdQC>
- [3] P. Nag, *Power Plant Engineering*. Tata McGraw-Hill, 2002. [Online]. Available: <https://books.google.co.za/books?id=Cv9LH4ckuEwC>
- [4] W. Hoffmann, “Pv solar electricity industry: Market growth and perspective,” *Solar energy materials and solar cells*, vol. 90, no. 18-19, pp. 3285–3311, 2006.
- [5] G. Pathak, B. Singh, and B. K. Panigrahi, “Grid synchronization of wind based microgrid,” in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, July 2016, pp. 1–6.
- [6] M. F. M. Arani and Y. A. R. I. Mohamed, “Analysis and impacts of implementing droop control in dfig-based wind turbines on microgrid/weak-grid stability,” *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 385–396, Jan 2015.
- [7] M. Nasir, H. A. Khan, A. Hussain, L. Mateen, and N. A. Zaffar, “Solar pv-based scalable dc microgrid for rural electrification in developing regions,” *IEEE Transactions on Sustainable Energy*, vol. 9, no. 1, pp. 390–399, Jan 2018.
- [8] M. Hamza, M. Shehroz, S. Fazal, M. Nasir, and H. A. Khan, “Design and analysis of solar pv based low-power low-voltage dc microgrid architectures for rural electrification,” in *2017 IEEE Power Energy Society General Meeting*, July 2017, pp. 1–5.
- [9] C. D., X. L., and Y. L., “DC voltage variation based autonomous control of DC microgrids,” *IEEE Transactions on Power Delivery*, vol. 28, no. 2, pp. 637–648, 2013.

- [10] J. Schönberger, R. Duke, and S. D. Round, “DC-bus signaling: A distributed control strategy for a hybrid renewable nanogrid,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, pp. 1453–1460, 2006.
- [11] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos, and D. Sáez, “A microgrid energy management system based on the rolling horizon strategy,” *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 996–1006, June 2013.
- [12] O. Hafez and K. Bhattacharya, “Optimal planning and design of a renewable energy based supply system for microgrids,” *Renewable Energy*, vol. 45, pp. 7–15, 2012.
- [13] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, “Microgrids management,” *IEEE Power and Energy Magazine*, vol. 6, no. 3, pp. 54–65, May 2008.
- [14] R. E. Sims, H.-H. Rogner, and K. Gregory, “Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation,” *Energy policy*, vol. 31, no. 13, pp. 1315–1326, 2003.
- [15] E. S. Rubin, C. Chen, and A. B. Rao, “Cost and performance of fossil fuel power plants with co2 capture and storage,” *Energy policy*, vol. 35, no. 9, pp. 4444–4454, 2007.
- [16] L. Jiaoyang, W. Yong, and W. Chengmin, “Research of photovoltaic grid-connected and islanded storage system in dc microgrid,” in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, May 2016, pp. 1764–1769.
- [17] P. Mohammadi and J. S. Moghani, “Double-input high-gain bidirectional dc-dc converter for hybrid energy storage systems in dc-micro grid,” in *2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC)*, Feb 2018, pp. 312–317.
- [18] X. Chang, F. Chen, Y. Li, Y. Wang, and C. Xu, “Improved power allocation strategy of hybrid energy storage system in islanding dc micro-grid,” *The Journal of Engineering*, vol. 2017, no. 13, pp. 1404–1407, 2017.
- [19] M. Wu, L. J. Sun, H. Zhang, W. Wang, and G. M. Luo, “Research on optimal storage capacity of dc micro-grid system in pv station,” *The Journal of Engineering*, vol. 2017, no. 13, pp. 859–864, 2017.

- [20] A. Skumanich and P. Mints, "Micro-grid and dg expansion: Key role of storage, projected global demand," in *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, June 2017, pp. 1–4.
- [21] J. Hakkim and L. Alias, "Photovoltaic micro-inverter in grid and islanded mode with restructured control adopting second order current algorithm," in *2014 International Conference on Advances in Green Energy (ICAGE)*, Dec 2014, pp. 158–164.
- [22] S. Nasr, M. Iordache, and M. Petit, "Smart micro-grid integration in dc railway systems," in *IEEE PES Innovative Smart Grid Technologies, Europe*, Oct 2014, pp. 1–6.
- [23] P. H. Huang, P. C. Liu, W. Xiao, and M. S. El Moursi, "A Novel Droop-Based Average Voltage Sharing Control Strategy for DC Microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1096–1106, 2015.
- [24] G. G. Facchinello, H. Mamede, L. L. Brighenti, S. L. Brockveld, W. D. Santos, and D. C. Martins, "Ac-ac dual active bridge converter for smart grid applications," in *2016 12th IEEE International Conference on Industry Applications (INDUSCON)*, Nov 2016, pp. 1–8.
- [25] M. Morawiec, A. Lewicki, and Z. Krzemiński, "Power electronic transformer for smart grid application," in *2015 First Workshop on Smart Grid and Renewable Energy (SGRE)*, March 2015, pp. 1–6.
- [26] B. R. de Almeida, D. de Souza Oliveira, and P. P. Praça, "A bidirectional single-stage three-phase rectifier with high-frequency isolation and power factor correction," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2016, pp. 60–65.
- [27] S. Chakraborty, M. D. Weiss, and M. G. Simoes, "Distributed intelligent energy management system for a single-phase high-frequency ac microgrid," *IEEE Transactions on Industrial electronics*, vol. 54, no. 1, pp. 97–109, 2007.
- [28] L. Ott, Y. Han, B. Wunder, J. Kaiser, F. Fersterra, M. Schulz, and M. März, "An advanced voltage droop control concept for grid-tied and autonomous dc microgrids," in *2015 IEEE International Telecommunications Energy Conference (INTELEC)*, Oct 2015, pp. 1–6.
- [29] F. Gonzalez-Longatt, B. S. Rajpurohit, J. L. R. Torres, and S. N. Singh, "Simulation platform for autonomous smart multi-terminal dc micro-grid," in *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, Nov 2016, pp. 630–635.

- [30] “Control strategies for DC networks: A systematic literature review,” *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 319–330, 2016.
- [31] A. Y. Saber and G. K. Venayagamoorthy, “Smart micro-grid optimization with controllable loads using particle swarm optimization,” in *2013 IEEE Power Energy Society General Meeting*, July 2013, pp. 1–5.
- [32] R. J. Wai, Y.-C. Huang, and Y.-C. Chen, “Design of intelligent long-term load forecasting with fuzzy neural network and particle swarm optimization,” in *2012 International Conference on Machine Learning and Cybernetics*, vol. 4, July 2012, pp. 1644–1650.
- [33] M. A. E. Elabbas, A. M. E. Awad, and S. F. Babikir, “Agent based load management for microgrid,” in *2017 International Conference on Communication, Control, Computing and Electronics Engineering (ICCCCEE)*, Jan 2017, pp. 1–6.
- [34] L. A. de Souza Ribeiro, O. R. Saavedra, S. L. de Lima, and J. G. de Matos, “Isolated micro-grids with renewable hybrid generation: The case of len # x00e7; # x00f3;is island,” *IEEE Transactions on Sustainable Energy*, vol. 2, no. 1, pp. 1–11, Jan 2011.
- [35] J. Schonbergerschonberger, R. Duke, and S. D. Round, “Dc-bus signaling: A distributed control strategy for a hybrid renewable nanogrid,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, pp. 1453–1460, Oct 2006.
- [36] L. H. P. N. Gunawardena and D. R. Nayanasinghe, “Networked dc nano-grid based on multi-port power converters,” in *TENCON 2017 - 2017 IEEE Region 10 Conference*, Nov 2017, pp. 2727–2732.
- [37] G. Manavalan, H. M. Tania, J. K. Patra, M. G. Poongothai, and S. Prema, “A closed loop system to stabilize a 24v solar dc nano grid,” in *2017 International Conference on Smart grids, Power and Advanced Control Engineering (ICSPACE)*, Aug 2017, pp. 177–182.
- [38] Y. T. Quek, W. L. Woo, and T. Logenthiran, “Smart sensing of loads in an extra low voltage dc pico-grid using machine learning techniques,” *IEEE Sensors Journal*, vol. 17, no. 23, pp. 7775–7783, Dec 2017.
- [39] N. Liu, X. Yu, W. Fan, C. Hu, T. Rui, Q. Chen, and Z. Jianhua, “Online energy sharing for nanogrid clusters: A lyapunov optimization approach,” *IEEE Transactions on Smart Grid*, pp. 1–1, 2017.

- [40] T. Morstyn, B. Hredzak, and V. G. Agelidis, "Control strategies for microgrids with distributed energy storage systems: An overview," *IEEE Transactions on Smart Grid*, pp. 1–1, 2016.
- [41] S. Sahoo, S. Mishra, and N. P. Padhy, "A decentralized adaptive droop based power management scheme in autonomous dc microgrid," in *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Oct 2016, pp. 1018–1022.
- [42] D. Wu, F. Tang, T. Dragicevic, J. M. Guerrero, and J. C. Vasquez, "Coordinated control based on bus-signaling and virtual inertia for islanded dc microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2627–2638, Nov 2015.
- [43] K. Sun, L. Zhang, Y. Xing, and J. M. Guerrero, "A distributed control strategy based on dc bus signaling for modular photovoltaic generation systems with battery energy storage," *IEEE Transactions on Power Electronics*, vol. 26, no. 10, pp. 3032–3045, Oct 2011.
- [44] L. Zhang, T. Wu, Y. Xing, K. Sun, and J. M. Guerrero, "Power control of dc microgrid using dc bus signaling," in *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2011, pp. 1926–1932.
- [45] C. M. Colson, M. H. Nehrir, and S. A. Pourmousavi, "Towards real-time microgrid power management using computational intelligence methods," in *IEEE PES General Meeting*, July 2010, pp. 1–8.
- [46] J. Li, G. Poulton, and G. James, "Agent-based distributed energy management," in *Australasian Joint Conference on Artificial Intelligence*. Springer, 2007, pp. 569–578.
- [47] A. R. Yasin, M. Ashraf, A. I. Bhatti, S. Ahmad, and M. Rashid, "Sliding mode control for efficient utilization of renewable energy sources in dc micro grid: A comparison with a linear pid controller," in *2016 International Conference and Exposition on Electrical and Power Engineering (EPE)*, Oct 2016, pp. 621–625.
- [48] J. Xiao, P. Wang, and L. Setyawan, "Hierarchical control of hybrid energy storage system in dc microgrids," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 8, pp. 4915–4924, Aug 2015.
- [49] M. Hamzeh, A. Ghazanfari, Y. A. R. I. Mohamed, and Y. Karimi, "Modeling and design of an oscillatory current-sharing control strategy in dc microgrids," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 6647–6657, Nov 2015.

- [50] A. A. A. Radwan and Y. A. R. I. Mohamed, "Linear active stabilization of converter-dominated dc microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 203–216, March 2012.
- [51] R. Majumder, B. Chaudhuri, A. Ghosh, R. Majumder, G. Ledwich, and F. Zare, "Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop," *IEEE Transactions on Power Systems*, vol. 25, no. 2, pp. 796–808, May 2010.
- [52] X. Lu, J. M. Guerrero, K. Sun, and J. C. Vasquez, "An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy," *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 1800–1812, April 2014.
- [53] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, and L. Huang, "State-of-charge balance using adaptive droop control for distributed energy storage systems in dc microgrid applications," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 6, pp. 2804–2815, June 2014.
- [54] D. Salomonsson, L. Soder, and A. Sannino, "An adaptive control system for a dc microgrid for data centers," *IEEE Transactions on Industry Applications*, vol. 44, no. 6, pp. 1910–1917, Nov 2008.
- [55] M. Sechilariu, B. Wang, and F. Locment, "Building integrated photovoltaic system with energy storage and smart grid communication," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1607–1618, April 2013.
- [56] C. N. Papadimitriou, V. A. Kleftakis, A. Rigas, and N. D. Hatziaargyriou, "A dc-microgrid control strategy using dc- bus signaling," in *MedPower 2014*, Nov 2014, pp. 1–8.
- [57] Y. K. Chen, Y. C. Wu, C. C. Song, and Y. S. Chen, "Design and implementation of energy management system with fuzzy control for dc microgrid systems," *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1563–1570, April 2013.
- [58] H. Kakigano, Y. Miura, and T. Ise, "Distribution voltage control for dc microgrids using fuzzy control and gain-scheduling technique," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2246–2258, May 2013.
- [59] M. El-Sharkh, A. Rahman, and M. Alam, "Evolutionary programming-based methodology for economical output power from pem fuel cell for micro-grid application," *Journal of power sources*, vol. 139, no. 1-2, pp. 165–169, 2005.

- [60] A. Dimeas and N. Hatziargyriou, "Agent based control for microgrids," in *Power Engineering Society General Meeting, 2007. IEEE*. IEEE, 2007, pp. 1–5.
- [61] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Cañizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jiménez-Estévez, and N. D. Hatziargyriou, "Trends in microgrid control," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1905–1919, July 2014.
- [62] J. C. Mankins, "Technology readiness levels," *White Paper, April*, vol. 6, 1995.
- [63] A. R. E. A. (ARENA), "Technology readiness levels for renewable energy sectors," 2014.
- [64] J. D. Navamani, K. Vijayakumar, A. Lavanya, and A. J. M. Raj, "Non-isolated high gain dc-dc converter for smart grid-a review," in *Journal of Physics: Conference Series*, vol. 1000, no. 1. IOP Publishing, 2018, p. 012061.
- [65] R. Sathishkumar, S. K. Kollimalla, and M. K. Mishra, "Dynamic energy management of micro grids using battery super capacitor combined storage," in *2012 Annual IEEE India Conference (INDICON)*, Dec 2012, pp. 1078–1083.
- [66] F. Krismer, "Modeling and optimization of bidirectional dual active bridge dc-dc converter topologies," 2010.
- [67] B. Zhao, Q. Song, W. Liu, and Y. Sun, "Overview of dual-active-bridge isolated bidirectional dc-dc converter for high-frequency-link power-conversion system," *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4091–4106, Aug 2014.
- [68] M. Kashif, "Bidirectional flyback dc-dc converter for hybrid electric vehicle: Utility, working and pspace computer model," in *2012 Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics*, Dec 2012, pp. 61–66.
- [69] A. A. Aboulmaga and A. Emadi, "Performance evaluation of the isolated bidirectional cuk converter with integrated magnetics," in *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551)*, vol. 2, June 2004, pp. 1557–1562 Vol.2.
- [70] D. Murthy-Bellur and M. K. Kazimierczuk, "Isolated two-transistor zeta converter with reduced transistor voltage stress," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 58, no. 1, pp. 41–45, Jan 2011.

- [71] R. M. Schupbach and J. C. Balda, "Comparing dc-dc converters for power management in hybrid electric vehicles," in *Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE International*, vol. 3, June 2003, pp. 1369–1374 vol.3.
- [72] H. S. H. Chung, W.-L. Cheung, and K. S. Tang, "A zcs bidirectional flyback dc/dc converter," *IEEE Transactions on Power Electronics*, vol. 19, no. 6, pp. 1426–1434, Nov 2004.
- [73] H. J. Choi, H. P. Park, and J. H. Jung, "Design methodology of dual active bridge converter for solid state transformer application in smart grid," in *2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, June 2015, pp. 196–201.
- [74] Y. C. Wang, Y. C. Wu, and T. L. Lee, "Design and implementation of a bidirectional isolated dual-active-bridge-based dc/dc converter with dual-phase-shift control for electric vehicle battery," in *2013 IEEE Energy Conversion Congress and Exposition*, Sept 2013, pp. 5468–5475.
- [75] Z. Wang and H. Li, "A soft switching three-phase current-fed bidirectional dc-dc converter with high efficiency over a wide input voltage range," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 669–684, Feb 2012.
- [76] Y. Shi, R. Li, Y. Xue, and H. Li, "Optimized operation of current-fed dual active bridge dc # x2013;dc converter for pv applications," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 6986–6995, Nov 2015.
- [77] F. Krismer, S. Round, and J. W. Kolar, "Performance optimization of a high current dual active bridge with a wide operating voltage range," in *2006 37th IEEE Power Electronics Specialists Conference*, June 2006, pp. 1–7.
- [78] M. Ortega, J. C. Lopez, and F. Jurado, "Design of dc/dc bidirectional converter based on dsp in renewable energy," *Prz. Elektrotech*, vol. 88, no. 9, pp. 261–265, 2012.
- [79] H. Bai and C. Mi, "Eliminate reactive power and increase system efficiency of isolated bidirectional dual-active-bridge dc # x2013;dc converters using novel dual-phase-shift control," *IEEE Transactions on Power Electronics*, vol. 23, no. 6, pp. 2905–2914, Nov 2008.
- [80] M. Ryu, D. Jung, J. Baek, and H. Kim, "An optimized design of bi-directional dual active bridge converter for low voltage battery charger," in *2014 16th International Power Electronics and Motion Control Conference and Exposition*, Sept 2014, pp. 177–183.

- [81] L. M. Miranda, D. Varajão, B. dos Santos, R. E. Araújo, C. L. Moreira, and J. A. P. Lopes, "Power flow control with bidirectional dual active bridge battery charger in low-voltage microgrids," in *2013 15th European Conference on Power Electronics and Applications (EPE)*, Sept 2013, pp. 1–10.
- [82] H. Qin and J. W. Kimball, "Generalized average modeling of dual active bridge dc # x2013;dc converter," *IEEE Transactions on Power Electronics*, vol. 27, no. 4, pp. 2078–2084, April 2012.
- [83] Q. Ye, R. Mo, and H. Li, "Stability analysis and improvement of a dual active bridge (dab) converter enabled dc microgrid based on a reduced-order low frequency model," in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept 2016, pp. 1–7.
- [84] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Progress in Natural Science*, vol. 19, no. 3, pp. 291–312, 2009.
- [85] M. Beaudin, H. Zareipour, A. Schellenberglobe, and W. Rosehart, "Energy storage for mitigating the variability of renewable electricity sources: An updated review," *Energy for sustainable development*, vol. 14, no. 4, pp. 302–314, 2010.
- [86] J. Leadbetter and L. G. Swan, "Selection of battery technology to support grid-integrated renewable electricity," *Journal of Power Sources*, vol. 216, pp. 376–386, 2012.
- [87] B. B. McKeon, J. Furukawa, and S. Fenstermacher, "Advanced lead # x2013;acid batteries and the development of grid-scale energy storage systems," *Proceedings of the IEEE*, vol. 102, no. 6, pp. 951–963, June 2014.
- [88] T. T. de Sousa, V. T. Arioli, C. S. Vieira, S. R. dos Santos, and A. P. França, "Comparison of different approaches for lead acid battery state of health estimation based on artificial neural networks algorithms," in *2016 IEEE Conference on Evolving and Adaptive Intelligent Systems (EAIS)*, May 2016, pp. 79–84.
- [89] R. Kerley, J. H. Hyun, and D. S. Ha, "Automotive lead-acid battery state-of-health monitoring system," in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Nov 2015, pp. 003 934–003 938.
- [90] G. L. Bressanini, T. D. C. Busarello, and A. Péres, "Design and implementation of lead-acid battery state-of-health and state-of-charge measurements," in *2017 Brazilian Power Electronics Conference (COBEP)*, Nov 2017, pp. 1–6.

- [91] M. J. Smith, D. T. Gladwin, and D. A. Stone, "Experimental analysis of the influence of high-frequency ripple currents on dynamic charge acceptance in lead-acid batteries," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Oct 2017, pp. 7140–7145.
- [92] Y. Parvini, A. Vahidi, and S. A. Fayazi, "Heuristic versus optimal charging of supercapacitors, lithium-ion, and lead-acid batteries: An efficiency point of view," *IEEE Transactions on Control Systems Technology*, vol. 26, no. 1, pp. 167–180, Jan 2018.
- [93] I. Seedadani and R. Wongsathan, "Fuzzy controller based maximum power point tracking technique of standalone photovoltaic module for lead-acid battery charging," in *2017 3rd International Conference on Control, Automation and Robotics (ICCAR)*, April 2017, pp. 598–601.
- [94] T. Zahid, K. Xu, and W. Li, "Machine learning an alternate technique to estimate the state of charge of energy storage devices," *Electronics Letters*, vol. 53, no. 25, pp. 1665–1666, 2017.
- [95] J. M. Lujano-Rojas, G. J. Osório, T. D. P. Mendes, and J. P. S. Catalao, "Stochastic modeling of lead-acid battery parameters," in *2016 51st International Universities Power Engineering Conference (UPEC)*, Sept 2016, pp. 1–5.
- [96] O. Pop, A. Taut, A. Grama, R. Fizesan, and E. Ceuca, "Pspice discharge model for simulation circuits with lead-acid battery," in *2017 40th International Spring Seminar on Electronics Technology (ISSE)*, May 2017, pp. 1–4.
- [97] Z. N. Bako, M. A. Tankari, G. Lefebvre, and A. S. Maiga, "Lead-acid battery behavior study and modelling based on the kinetic battery model approach," in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, Nov 2016, pp. 673–677.
- [98] B. Diouf and R. Pode, "Potential of lithium-ion batteries in renewable energy," *Renewable Energy*, vol. 76, pp. 375–380, 2015.
- [99] K. Divya and J. Østergaard, "Battery energy storage technology for power systems—an overview," *Electric Power Systems Research*, vol. 79, no. 4, pp. 511–520, 2009.
- [100] O. M. Toledo, D. Oliveira Filho, and A. S. A. C. Diniz, "Distributed photovoltaic generation and energy storage systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 506–511, 2010.

- [101] M. M. Hoque, M. A. Hannan, and A. Mohamed, "Optimal cc-cv charging of lithium-ion battery for charge equalization controller," in *2016 International Conference on Advances in Electrical, Electronic and Systems Engineering (ICAEES)*, Nov 2016, pp. 610–615.
- [102] C. W. Lan, S. S. Lin, S. Y. Syue, H. Y. Hsu, T. C. Huang, and K. H. Tan, "Development of an intelligent lithium-ion battery-charging management system for electric vehicle," in *2017 International Conference on Applied System Innovation (ICASI)*, May 2017, pp. 1744–1746.
- [103] M. Chen and G. A. Rincon-Mora, "Accurate, compact, and power-efficient li-ion battery charger circuit," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 53, no. 11, pp. 1180–1184, Nov 2006.
- [104] T. Hatta, "Applications of sodium-sulfur batteries," in *PES T D 2012*, May 2012, pp. 1–3.
- [105] K. Saruta, "Long-term performance of sodium sulfur battery," in *2016 IEEE 2nd Annual Southern Power Electronics Conference (SPEC)*, Dec 2016, pp. 1–5.
- [106] F. Chen, B. Ji-jun, Z. Yu, L. Yu, and P. Zheng-rui, "Design and application of energy management system for sodium sulfur battery," in *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2)*, Nov 2017, pp. 1–6.
- [107] B. P. Roberts, "Sodium-sulfur (nas) batteries for utility energy storage applications," in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, July 2008, pp. 1–2.
- [108] T. A. Nguyen, M. L. Crow, and A. C. Elmore, "Optimal sizing of a vanadium redox battery system for microgrid systems," *IEEE transactions on sustainable energy*, vol. 6, no. 3, pp. 729–737, 2015.
- [109] T. A. Nguyen, X. Qiu, J. D. Guggenberger II, M. L. Crow, and A. C. Elmore, "Performance characterization for photovoltaic-vanadium redox battery microgrid systems," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1379–1388, 2014.
- [110] N. M. Nizam, M. H. Zulkhifli, A. C. Khor, M. R. Mohamed, and M. H. Sulaiman, "Design and development of vanadium redox flow battery (v-rfb) cell stack," in *4th IET Clean Energy and Technology Conference (CEAT 2016)*, Nov 2016, pp. 1–7.

- [111] Q. Wang, C. Shen, K. Zhang, and L. Zheng, "Super-capacitor and li-polymer battery hybrid energy storage for kinetic energy harvesting applications," in *2017 IEEE Conference on Energy Conversion (CENCON)*, Oct 2017, pp. 73–77.
- [112] H. Marzougui, A. Kadri, M. Amari, and F. Bacha, "Frequency separation based energy management strategy for fuel cell electrical vehicle with super-capacitor storage system," in *2018 9th International Renewable Energy Congress (IREC)*, March 2018, pp. 1–6.
- [113] B. Kaitao, A. Quntao, D. Jiandong, and S. Li, "Analysis and implementation of an enhanced modular multilevel dc/dc converter for super capacitor energy storage system," in *2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, Aug 2017, pp. 1–6.
- [114] C. M. Shepherd, "Design of primary and secondary cells ii. an equation describing battery discharge," *Journal of the Electrochemical Society*, vol. 112, no. 7, pp. 657–664, 1965.
- [115] H. Bode, "Lead-acid batteries," 1977.
- [116] R. Haddad, A. El Shahat, and Y. Kalaani, "Lead acid battery modeling for pv applications," *Journal of Electrical Engineering*, vol. 15, p. 17, 2015.
- [117] R. A. Jackey, "A simple, effective lead-acid battery modeling process for electrical system component selection," SAE Technical Paper, Tech. Rep., 2007.
- [118] C. Moo, K. Ng, Y. Chen, and Y. Hsieh, "State-of-charge estimation with open-circuit-voltage for lead-acid batteries," in *Power Conversion Conference-Nagoya, 2007. PCC'07.* IEEE, 2007, pp. 758–762.
- [119] S. Sato and A. Kawamura, "A new estimation method of state of charge using terminal voltage and internal resistance for lead acid battery," in *Power Conversion Conference, 2002. PCC-Osaka 2002. Proceedings of the*, vol. 2. IEEE, 2002, pp. 565–570.
- [120] M. Coleman, C. K. Lee, C. Zhu, and W. G. Hurley, "State-of-charge determination from emf voltage estimation: Using impedance, terminal voltage, and current for lead-acid and lithium-ion batteries," *IEEE Transactions on industrial electronics*, vol. 54, no. 5, pp. 2550–2557, 2007.
- [121] A. Degla, M. Chikh, A. Chouder, F. Bouchafaa, and A. Taallah, "Update battery model for photovoltaic application based on comparative analysis and parameter identification of lead-acid battery models behaviour," *IET Renewable Power Generation*, vol. 12, no. 4, pp. 484–493, 2017.

-
- [122] J. Copetti, E. Lorenzo, and F. Chenlo, “A general battery model for pv system simulation,” *Progress in Photovoltaics: research and applications*, vol. 1, no. 4, pp. 283–292, 1993.

Appendix A

Dual Active Bridge Magnetic Component Design

A.1 Introduction

As demonstrated in the main body of this work the magnetic component is the critical component of the Dual Active Bridge (DAB) bi-directional DC-DC converter. This appendix will present the design methodology and finalised designs for the leakage inductor and high-frequency transformer. Litz wire, foil-based and planar designs were evaluated as possible construction techniques for the magnetic component. The planar based design was selected due to the ease of construction and 99% coupling of the HF transformer.

A.2 Leakage inductor design

The leakage inductor L_s [H] is the energy storage element of the DAB converter. The required leakage inductance for a particular power transfer is given by equation (A.1) discussed in Section 5.3 .

$$\frac{10 R_s}{2\pi f_s} \leq L_s \leq \frac{n V_1 V_{gr}}{8 f_s P_{max}}. \quad (\text{A.1})$$

where R_s [Ω] is the resistive losses on the coil, f_s [Hz] is the switching frequency, n is the turns ratio, V_1 [V] is the input voltage, V_2 [V] is the output voltage and P_{max} [W] is the power transferred.

Due to the low energy storage capability of the ferrite material the leakage inductor is gapped to add additional storage capability. The methodology for determining the length of the required airgap begins by computing the amount of work done in a single switching cycle. The energy in a single switching cycle is given as:

$$W_{pp} = \frac{P_{max}}{f_s} \quad (\text{A.2})$$

where W_{pp} [J] is the energy per a pulse. The work done by the core can be given as:

$$W_c = \frac{1}{2} \frac{B_m^2 l_e A_c}{\mu_0 \mu_r} \quad (\text{A.3})$$

where W_c [J] is energy stored in the core, B_m [T] is maximum flux density of the core, l_e [m] is the mean magnetic path length and A_c [m²] is the cross sectional area of the core. The required energy that the airgap needs to store is expressed as:

$$W_{ag} = W_{pp} - W_c = \frac{1}{2} \frac{B_m^2 l_{ag} A_c}{\mu_0} \quad (\text{A.4})$$

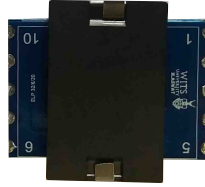
where W_{ag} [J] is the energy stored in the air gap, l_{ag} [m] is the length of the air gap. The required number of turns N to achieve the required inductance is given as per equation (A.5)

$$\begin{aligned} N &= \sqrt{L_s R} \\ &= \sqrt{L_s \left(\frac{l_e}{A_c \mu_0 \mu_r} + \frac{l_{ag}}{A_c \mu_0} \right)} \end{aligned} \quad (\text{A.5})$$

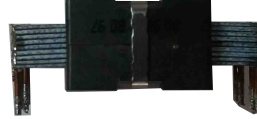
Using the above methodology the parameters for the 1.8 μH inductor discussed in Section 5.3 is summarised in Table A.1. An image of the designed planar inductor is shown in Figure A.1. These images show how multiple double layer stacks is used to fill the window area and decrease the conduction losses.

Table A.1: Specifications of the designed leakage inductor L_s

Description	Value	Description	Value
Core	ELP 32/6/20	Material	N97
l_e	41.4 mm	A_c	130 mm ²
l_{ag}	0.4 mm	N	3
R_{AC}	10.8 m. Ω		



(a) Top view of the built inductor.



(b) Side view of the built inductor

Figure A.1: Image of the constructed inductor

A.3 High frequency transformer design

This section will go through the process used to design the high-frequency transformer. The transformer is designed using Faraday's law as shown in equation (A.6)

$$\begin{aligned}
 V_p &= N_p \frac{d\phi}{dt} \\
 N_p &= \frac{B A_c}{dt} \\
 &= \frac{V_p D T_s}{\Delta B A_c}
 \end{aligned} \tag{A.6}$$

where N_p is number of turns on the primary, V_p is the voltage on the primary side of the transformer, D is the on ratio of the transformer, $\Delta B = 2 B_m$ is maximum change in flux density and $T_s [s]$ is the switching period. The specifications for the designed and constructed transformer used in the DAB is shown in Table A.2. A photo of the designed transformer can be seen in Figure A.2.

Table A.2: Specifications of the designed high-frequency transformer

Description	Value	Description	Value
Core	ELP 32/6/20	Material	N97
A_c	130 mm ²	V_p	12 V
V_s	12 V	D	0.5
N_p	2	N_s	2
L_p	9.91 μ H	L_s	9.85 μ H
R_{AC1}	21.5 m Ω	R_{AC2}	21.2 m Ω
Coupling Factor	99.2 %		



Figure A.2: Photo of the built planar transformer.

A.4 Conclusion

The magnetic component was designed using a planar construction technique. The advantage of this technique is the good coupling between the primary and secondary coils of the transformer. In addition to this, planar transformers are easier to construct in comparison to Litz wire and foil-based windings.

Appendix B

Spice Simulation

B.1 Introduction

A spice simulation was created to evaluate the Dual Active Bridge (DAB) converter. The simulation tool allows for permutations of the magnetic component and effects of parasitics to be evaluated. A snapshot of the simulation diagram is shown in Figure B.1. This simulation assisted in the designing of the DC bus and prototype converter discussed in Appendices C & E. The simulation was integral in understanding the limitations of the converter and the establishing requirements for the DAB to interface to the battery and PeCo grid.

B.2 Conclusion

The developed simulation tool captures parasitic aspects of the DAB, allows for design requirements and recommendations to be established. In addition to the establishment of design requirements, the simulation tool gives the capability to evaluate design changes rapidly.

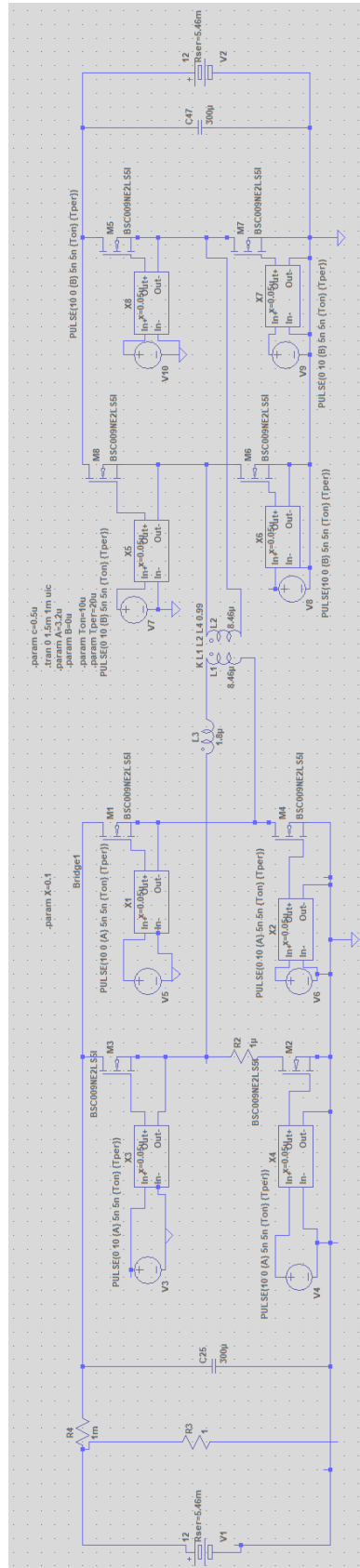


Figure B.1: LT Spice simulation used to test and develop a DAB converter.

Appendix C

Dual Active Bridge Prototype

C.1 Introduction

The prototype Dual Active Bridge (DAB) converter built in Figure C.2 is the third and final revision of the built converter. This appendix contains the schematic diagrams for the converter. The overview of the converter is shown in Figure C.2. The sub-circuits are the H-Bridge circuit, the MCU circuit and power supply circuit. The H-Bridge circuit consists of the high side driving shown in C.4, the protection circuit in Figure C.5 and the isolated analogue measurement shown in Figure C.6. The power supply circuit in Figure C.8 is responsible for supplying the integrated chips on each H-Bridge with isolated supplies and reference voltages. The MCU circuit in Figure C.8 is responsible for the driving scheme and control algorithm implementation.

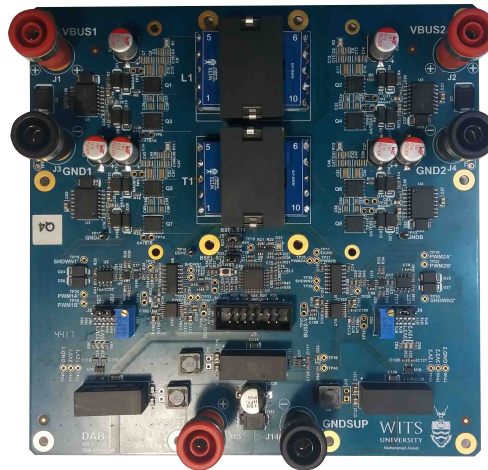


Figure C.1: Prototype DAB DC-DC converter.

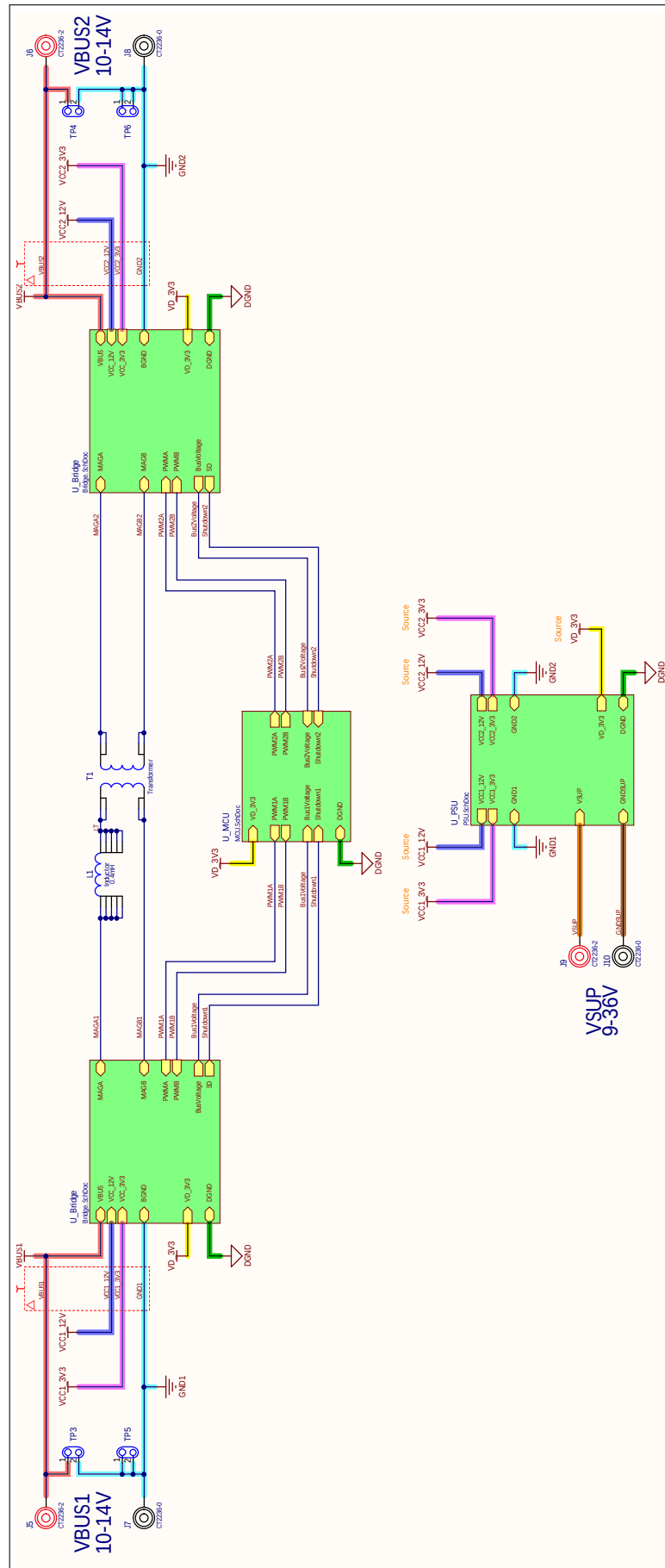


Figure C.2: Overview of the DAB converter

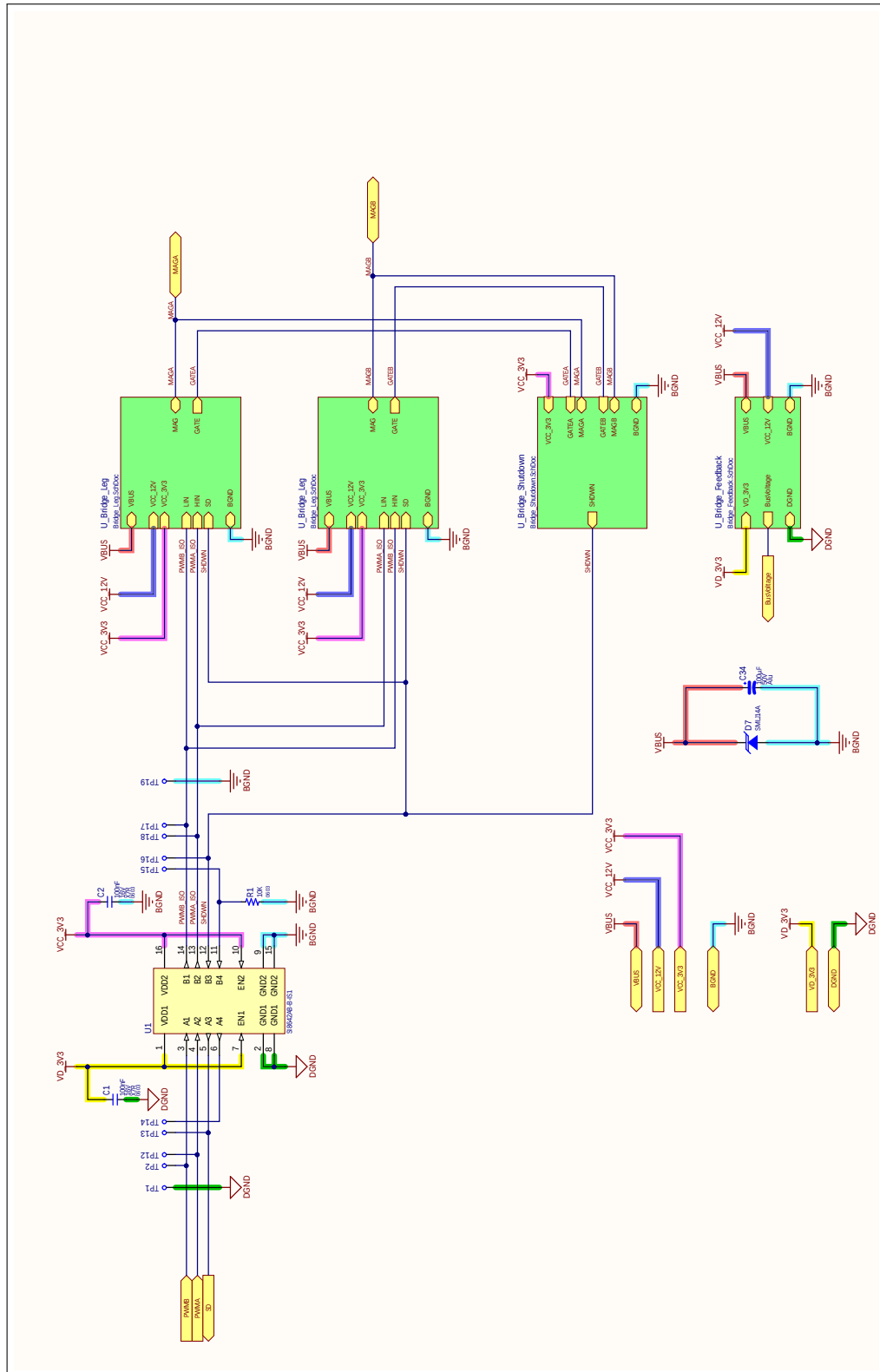


Figure C.3: Overview of the H-Bridge Driving circuit.

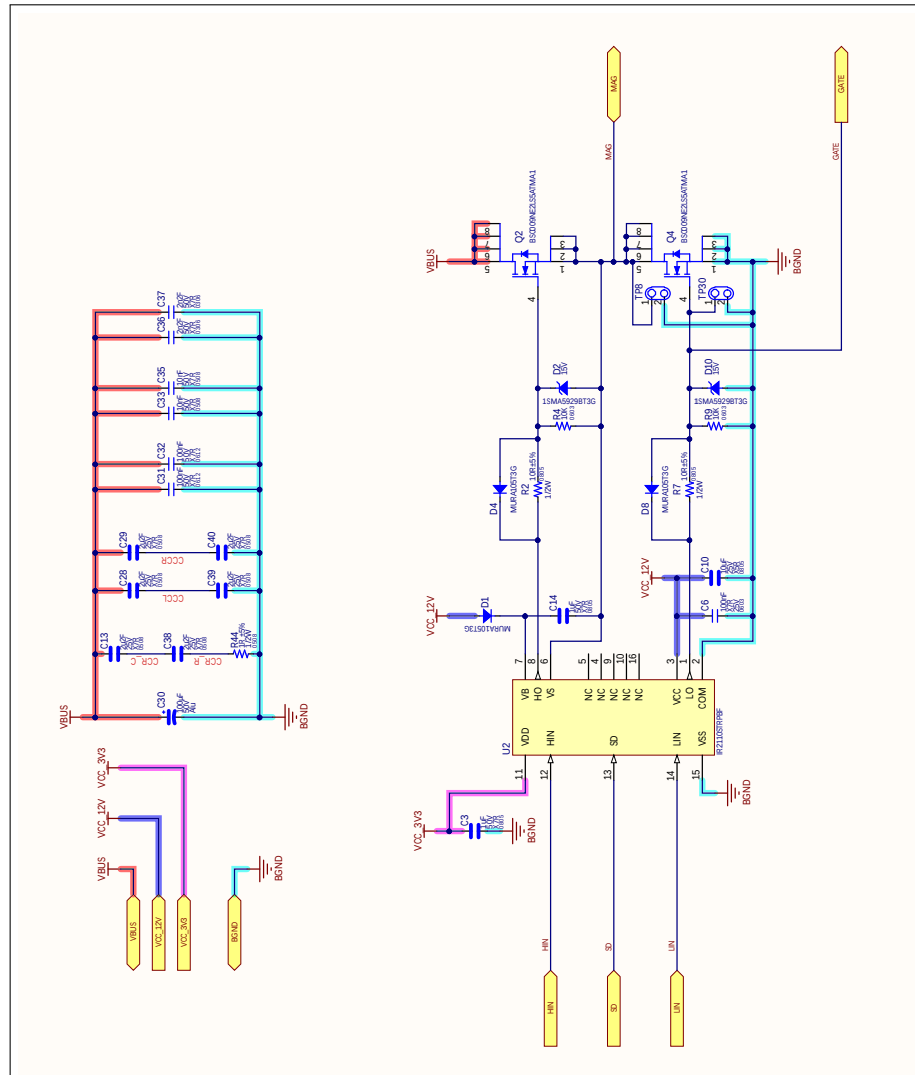


Figure C.4: High side driver and DC bus capacitors for the half bridge circuit.

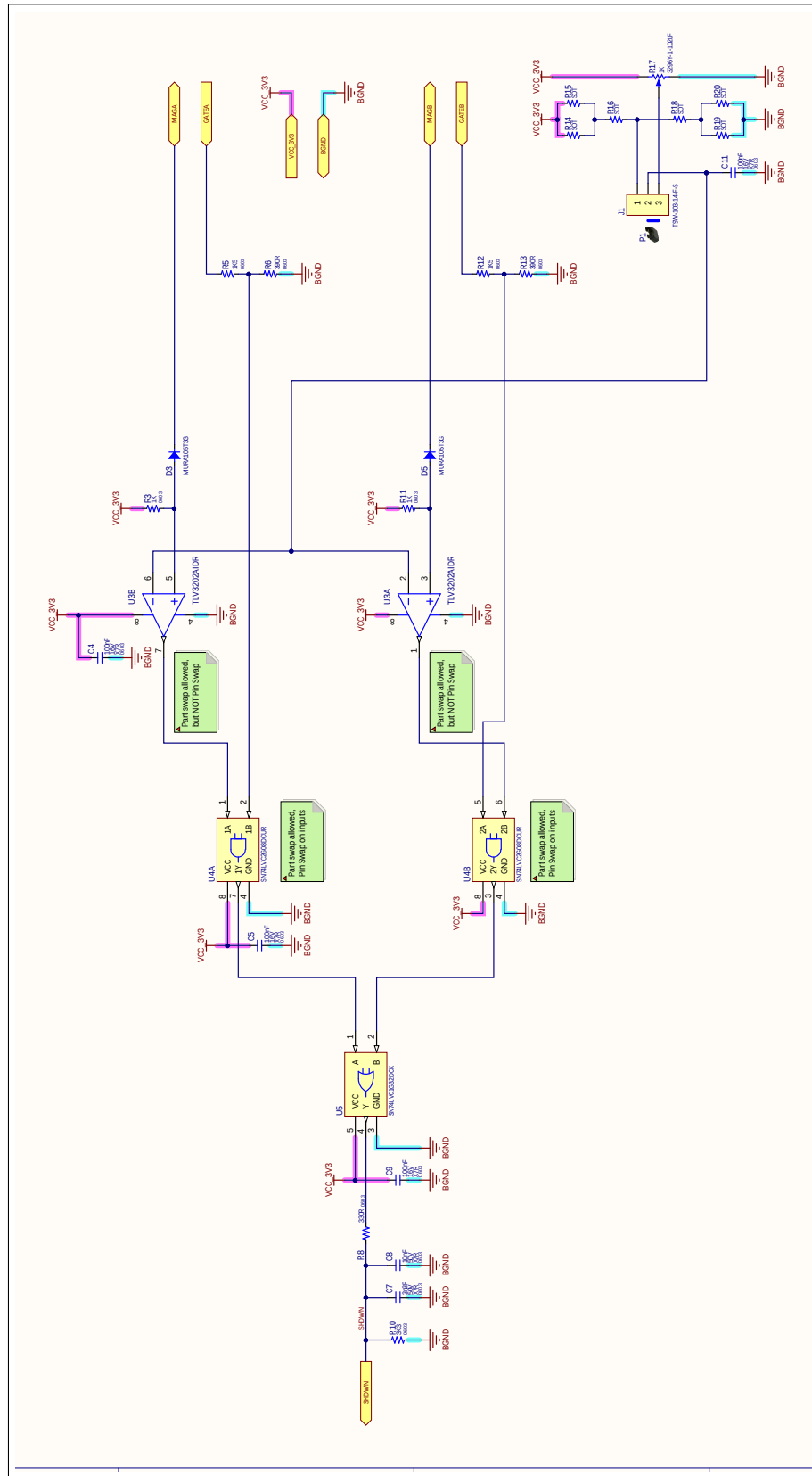


Figure C.5: Bridge protection circuit for one half bridge.

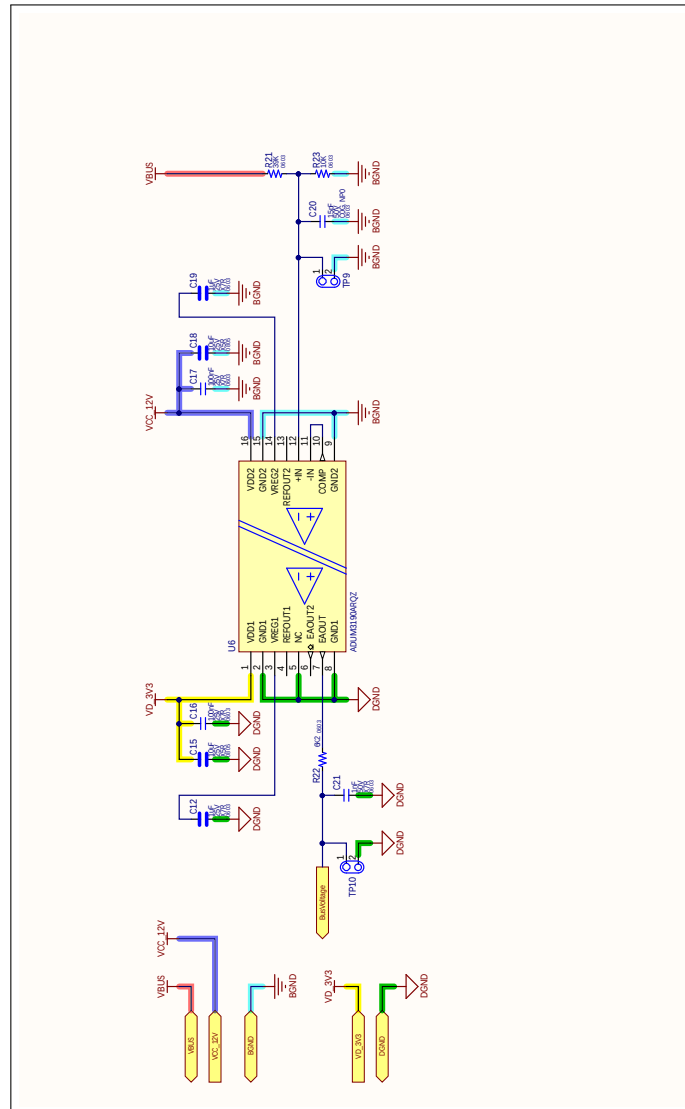


Figure C.6: Isolated analogue feed-back diagram.

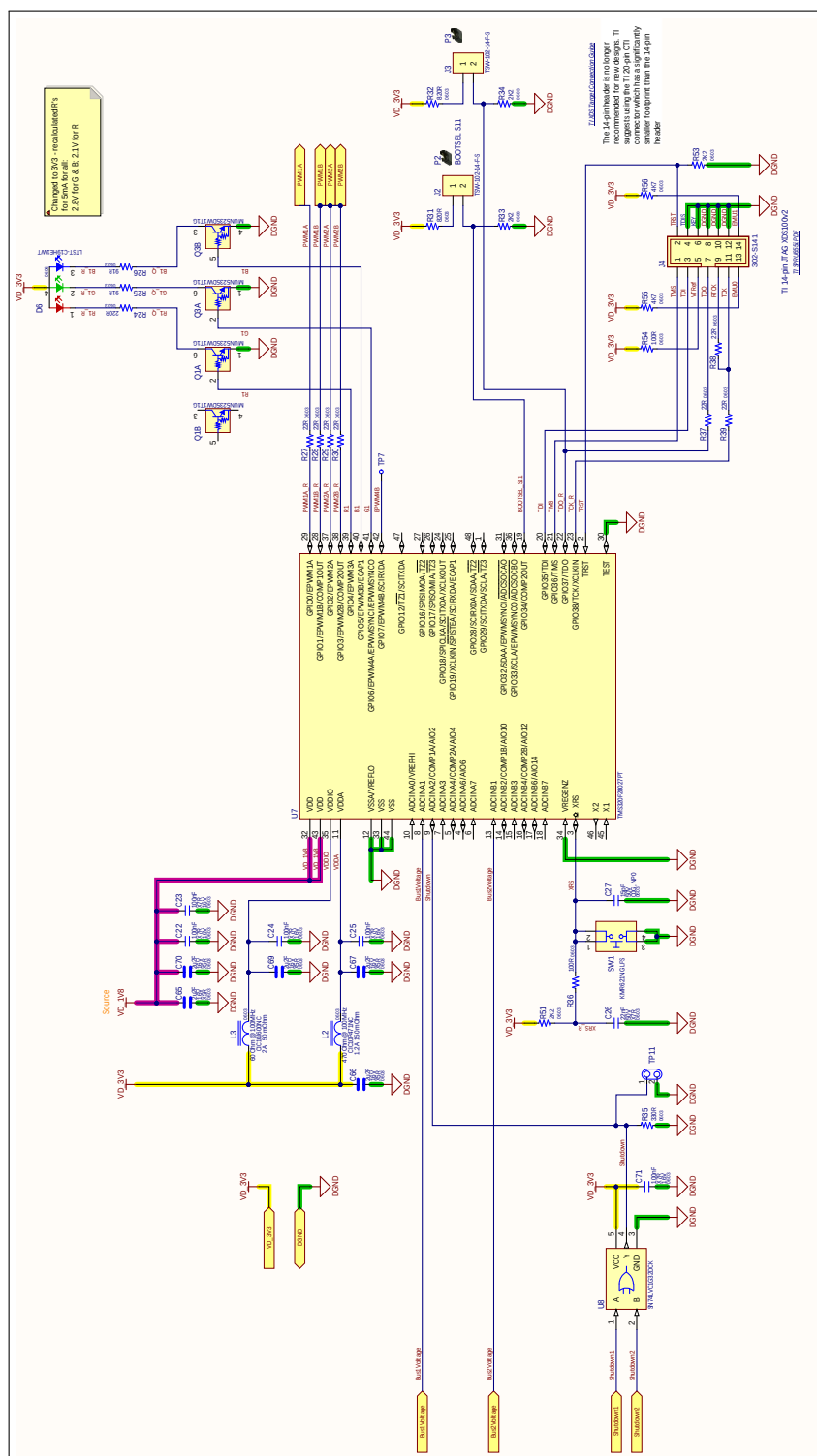


Figure C.7: MCU circuit diagram.

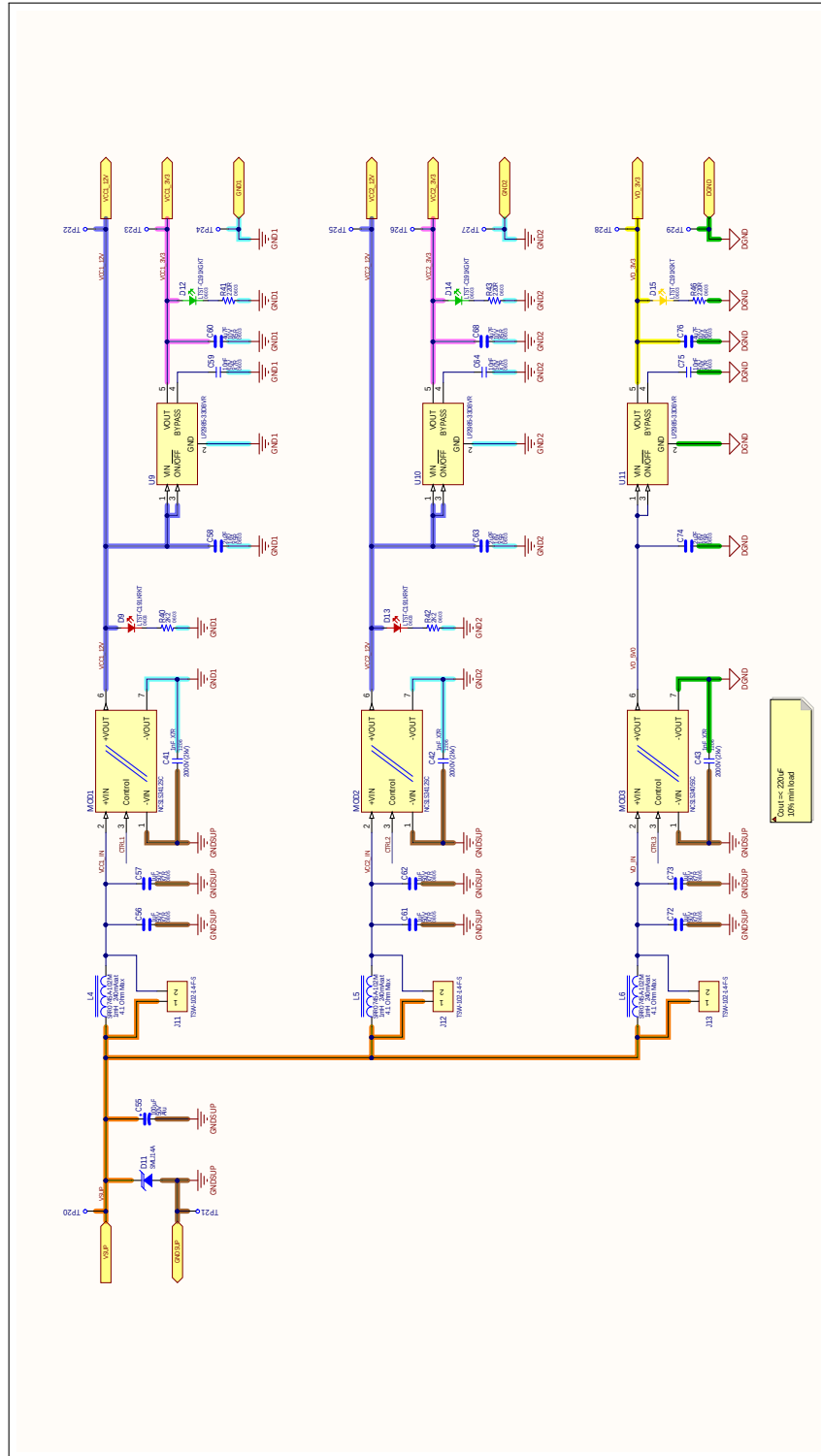


Figure C.8: Power supply circuit diagram for supply integrated circuits.

Appendix D

Thermography of the Dual Active Bridge

D.1 Introduction

The prototype Dual Active Bridge (DAB) shown in Appendix C consists of an 8 layer board with a specific focus on using multiple layers for heat dissipation and conduction loss reduction. Although this is advantageous and desired in a power converter it makes isolating the source of losses difficult. To establish the source of losses a thermal camera and video recorder set-up was used as shown in Figure D.1. The experimental setup allows for the source of heat to be mapped as a function of time before the board reaches a steady state temperature.

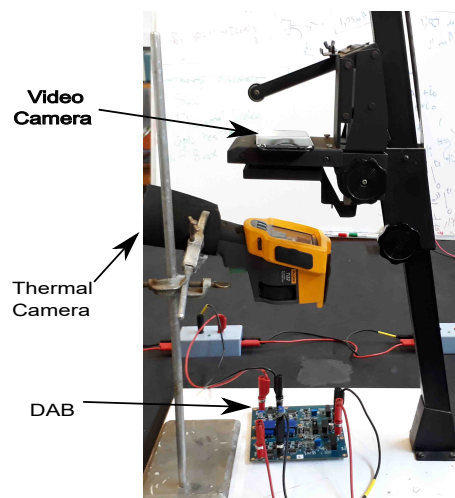


Figure D.1: Test set-up used to thermally map the DAB.



Figure D.2: Thermal snapshot at the beginning of recording.



Figure D.3: Snapshot of thermal recording at 43 s.

The snapshot at the beginning of the recording is shown in Figure D.2. This figure shows the temperature at beginning of the recording is uniform and at room temperature. Figure D.3 shows that the transformer coils heat up before the core. The heat from the coils is transferred to the core as the window area is completely filled. The steady state temperature of the converter can be seen in Figure D.4. The anomaly seen on the inductor which seems to have a cold spot is due to the matt blue tape used to provide a uniform emissivity lifting as the glue on the tape is no longer able to provide adhesion at this temperature.

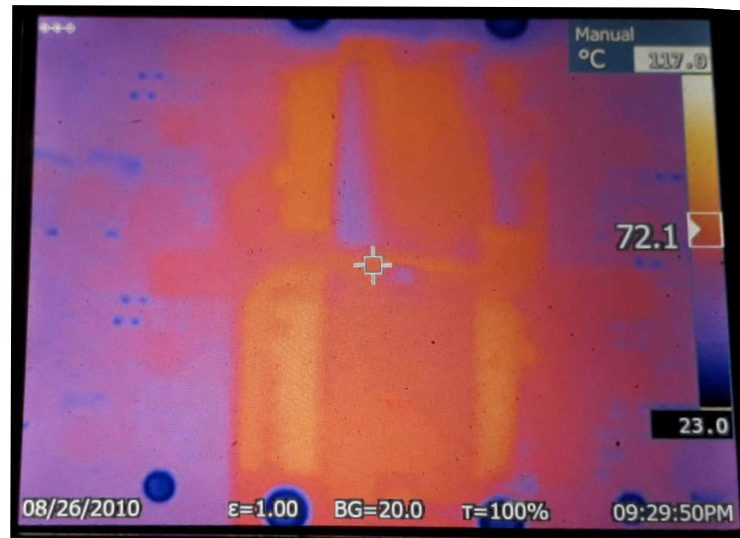


Figure D.4: Steady state temperature of the DAB after 8 minutes.

D.2 Conclusion

The thermography used to determine the source of loss was successfully able to establish the loss source on the DAB converter. The coils of the planar magnetic components were identified as the lossy component on the board. This finding implies that more work is required to reduce the AC resistance of the coils.

Appendix E

Designing a Filter Network for High Current DC-DC Converters on a Low Voltage DC Grid (SAUPEC 2018 Paper)

Abstract

A design methodology for a filter network of a DC-DC converter operating on a low voltage DC grid is presented. The design methodology aims to offer a simplistic method to design filters for these converters. The resulting filter network will reduce the voltage bus pollution that arises due to high current switch mode converters and allow for control strategies based on the bus voltage to be applied. The performance of the designed filter network is validated using Spice simulations and experimentation.

E.1 Introduction

This document presents a filter network for high current DC-DC converters operating on LVLP DC grids. The design of this network consists of a two stage design process. The first stage estimates the bulk capacitance to keep the DC bus stable and the second stage reduces the voltage transients that arise due to the parasitic elements on the bus.

DC-DC converters form the core component in distributed DC power systems as they are responsible for modulating power flow on the grid. The design of DC-DC converters is fairly well developed but there is still a requirement to develop filter networks for DC-DC converters operating on these grids. As the nominal bus voltage decreases the sensitivity to voltage transients arising from switch mode converters switching high currents at high frequencies increases. This increase in sensitivity due to transient voltages makes filter networks extremely crucial to ensure a clean stable DC bus. A filter network will be designed and tested experimentally on a 12 V LVLP grid.

E.2 Background

Isolated Low Voltage Low Power (LVLP) distributed DC grids using renewable energy is a viable solution for environmentally friendly rural electrification[1–5]. A diagram of a LVLP distributed DC grid shown in Figure E.1 is made up of three types of functional units: a source unit, a storage unit and a load unit. A source unit consists of an electricity generation element such as a Photo-Voltaic (PV) panel or wind turbine which is cascaded with a unidirectional DC-DC converter. Source units use unidirectional converters as they only supply energy. Storage units in contrast are made up of batteries cascaded with bidirectional DC-DC converters. These units are required to use bidirectional converters as they supply energy when there is a deficit and absorb energy when there is a surplus.

The distributed system in Figure E.1 has no intercommunication between the various building units and relies on the grid voltage upon which control decisions are made [4, 7, 8, 30]. A grid where the bus voltage has a large ripple or high frequency noise may cause the control strategy for these distributed grids to break down.

The most simplistic filter network for switch mode converters are input and output capacitors. Reference [9–11] provides filter capacitor guidelines dependant on the allowable ripple voltage and capacitor hold time. The effects on ripple voltage by ESR is highlighted in [10, 11] and must be considered when designing these filters. An LC filter can be added to provide better performance in comparison to the basic capacitor but comes at the added disadvantage of having a higher steady state ripple [12].

Various converter topologies such as the flyback, buck boost, Dual Active Bridge (DAB) are used on distributed power system [4, 13, 14]. The DAB provides a high power rating as well bi-directional capabilities in comparison to other switch-mode converter topologies [67]. A simplistic version of a DAB is shown in Figure E.3 and consists of two magnetically coupled H-Bridges. As this topology provides a high power rating and bi-directional capabilities it is the selected topology which will be used to validate the design methodology. This paper will not focus on the design or control aspects required to make the DAB operate on a LVLP DC grid but only the filter network that needs to be realised for the converter to operate in steady state condition at constant power transfer.

A key limitation when designing a high current DC-DC converter is the parasitic elements of the DC bus [16]. These elements lead to voltage transients and high

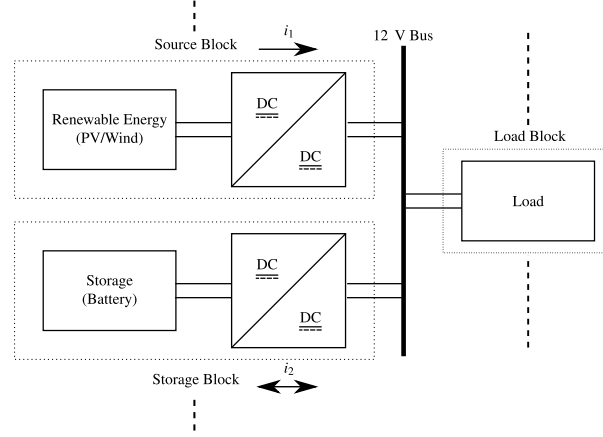


Figure E.1: Block diagram representation showing the key components on the LVLP Picogrid where i_1 & i_2 are the DC-DC converter current flow directions.

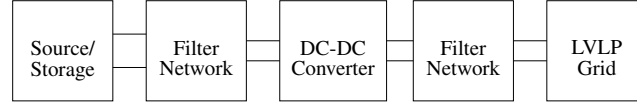


Figure E.2: Core components for an arbitrary DC-DC converter where the filter network is a low-pass filter.

frequency noise specifically due to parasitic inductances. This limits the power rating of a single DC-DC converter on an LVLP DC grid without the use of additional harmonic suppression techniques. Passive methods such as high order power filters can be used to mitigate this. An alternative to the classical passive methods is active harmonic suppression presented in [17]. Active methods can reduce the order of the overall filtering network hence reducing the number of passive components however they require complex control strategies.

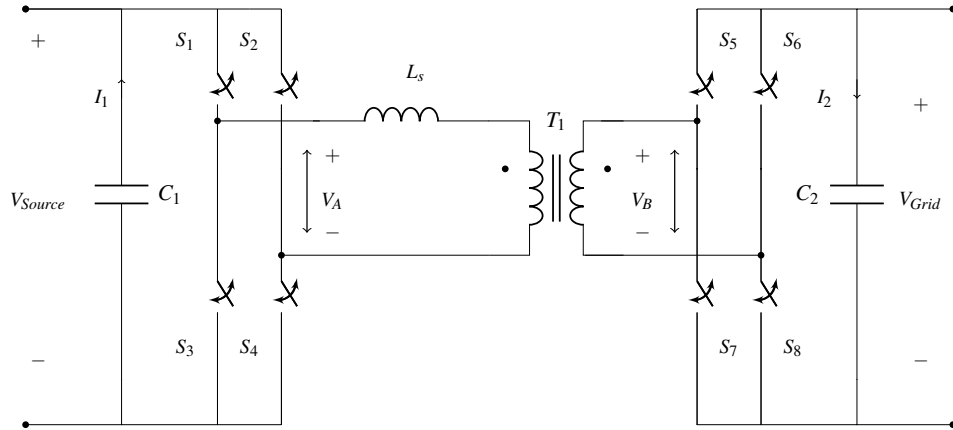


Figure E.3: Basic circuit elements for a DAB.

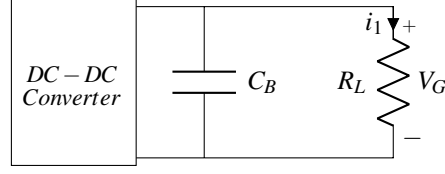


Figure E.4: Simplified RC model used to size the bulk capacitor where V_G is the nominal grid voltage and i_1 is the maximum current the converter can source.

E.3 Bulk capacitance

The design process begins by estimating the required capacitance to control the ripple voltage on the bus. A simplified RC model shown in Figure E.4 is used to establish the capacitance value. The bulk capacitor is responsible for ensuring the bus voltage does not drop below the ripple factor defined in (E.2) within one switching cycle. The RC time constant (τ) can be related to the switching frequency by (E.1).

$$\tau = R_L C_B = \frac{1}{f_s} \quad (\text{E.1})$$

where R_L [Ω] is the load resistance, C_B [F] is the bulk capacitor and f_s [Hz] is the switching frequency. The bus degradation due to insufficient capacitance can be modelled using a ripple factor (RF) given by:

$$RF = \frac{V_{P-P}}{V_{Ave}} = e^{-f_s R_L C_B} \quad (\text{E.2})$$

where V_{P-P} is the peak to peak voltage on the the DC bus and V_{Ave} is the DC value of the bus. Figure E.5 shows the relationship between the estimated RF using (E.2) and the simulated ripple factor of a DAB. After 5τ little advantage is obtained when trying to reduce the ripple factor. Using the power rating of the converter P_{sys} [W] and grid voltage V_G [V] the required bulk capacitor can be established using (E.3).

$$C_B > \frac{5 P_{sys}}{V_G^2 f_s} \quad (\text{E.3})$$

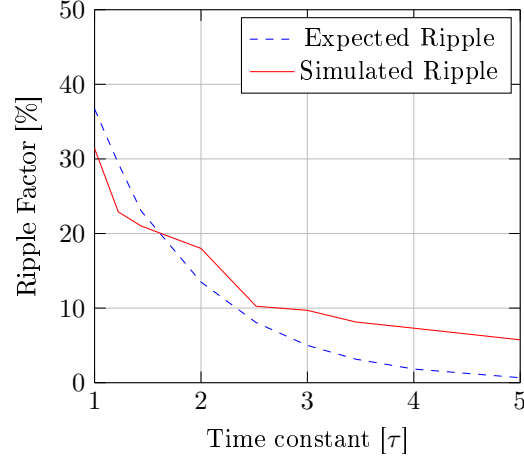
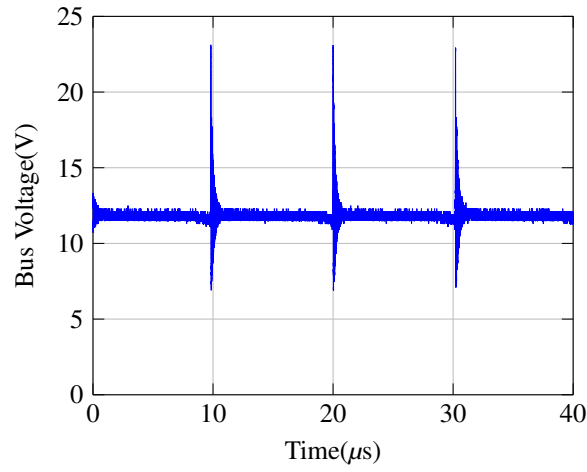


Figure E.5: Expected and simulated ripple voltage of the DAB shown in Figure E.3 using simplified RC approach to estimate required bulk capacitance under constant power draw while increasing the output capacitance at a constant 50 kHz switching frequency with grid parameters as per Table E.1.

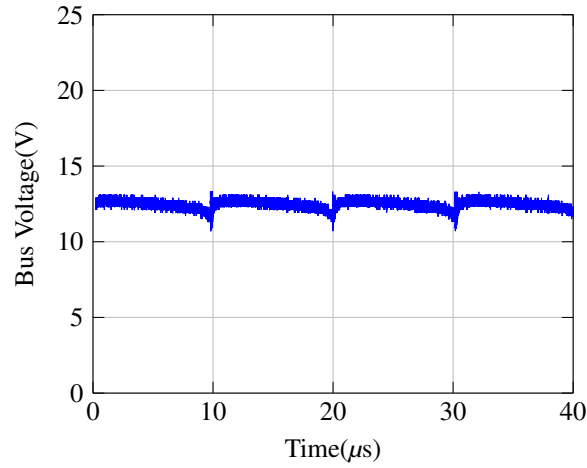
E.4 Transient Voltage Suppression

Voltage spikes shown in Figure E.6 occur due to the cyclic commutation of current from charging to discharging of the bulk capacitor. In order to understand the cause of these spikes it is necessary to consider the non ideal capacitor due to the parasitic elements. The non ideal model shown in Figure E.7 captures the behaviour of a capacitor due to parasitic inductances and resistance. The non ideal model shows that any high current commutation on the capacitor current path will lead to voltage spikes due the parasitic inductances. These voltage spikes pose significant problems on DC-DC converters used in distributed DC grids as the voltage bus becomes polluted. This also increases switching losses which places additional strain on the components reducing its lifespan.

To suppress these voltages it is necessary to apply additional capacitors in parallel with the bulk capacitance. These capacitors are required to have both a low ESL and low ESR. This can be achieved using ceramic capacitors. The recommendation is that 3 values of the high speed capacitors are selected each one order magnitude less than the other to ensure that both the ESR and ESL of the the equivalent capacitance is reduced to form a more ideal capacitor. The ESL and ESR reduction only occurs if $L_B > L_1$ & $R_B > R_1$ and $L_{N-1} > L_N$ & $R_{N-1} > R_N$. The selection of these capacitors is summarised in (E.4).



(a) Bus voltage using oversized 10 mF capacitor.



(b) Bus voltage when using sizing capacitors in Table E.2

Figure E.6: Measured bus voltage when drawing 30 W from the DAB converter using a resistor

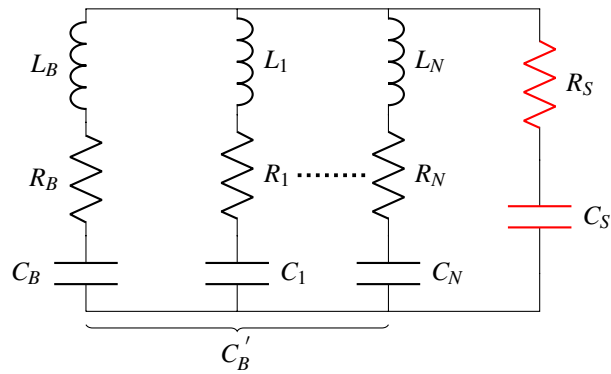


Figure E.7: Method for idealising a non-ideal capacitor using capacitor paralleling to form a bank (C'_B).

$$\begin{aligned} C_1 &= \frac{C_B}{10} \\ C_2 &= \frac{C_1}{10} \\ C_3 &= \frac{C_2}{10} \end{aligned} \tag{E.4}$$

In addition to selecting low ESL and low ESR capacitors an RC snubber is inserted on the bank to damp high frequencies. The required capacitor is expressed using (E.5). This ensures that the impedance of the capacitor is $-1j \Omega$ at the switching frequency which offers a very low impedance path to ground for harmonics much greater than f_s . The selected impedance of $-1j \Omega$ is selected to ensure that the required capacitance can be realised using ceramic capacitors due to their low ESL. In addition to the capacitor the R_s is set to 0.1Ω for damping. The high frequency damping effect of the RC snubber is shown in Figure E.8.

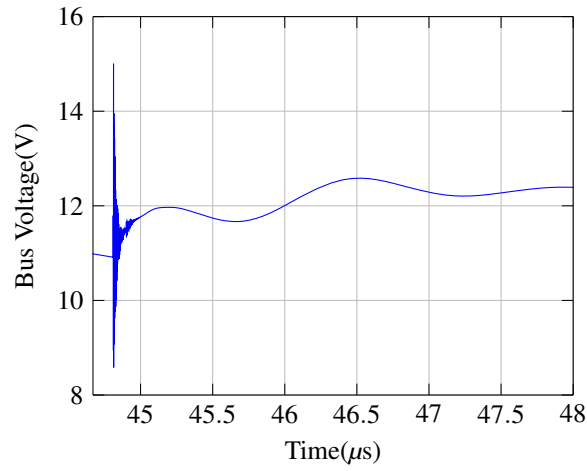
$$C_s = \frac{1}{2\pi f_s} \tag{E.5}$$

E.5 Pi Filter

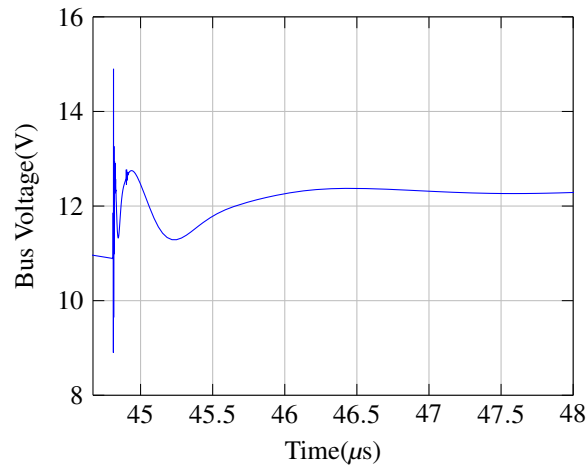
A low pass LC filter is added after the bulk capacitor to form a pi network as shown in Figure E.9 . The cut-off frequency ($f_c [Hz]$) of the LC network is given by:

$$f_c = \frac{1}{2\pi\sqrt{L_F C_B}} \tag{E.6}$$

The capacitors (C_B) are identical which forms a symmetrical pi network. This symmetry is advantageous in bidirectional converters where power flows both into and out of the device. The effects due to the current commutation occur at frequencies greater than the switching frequency. The cut off frequency of the LC low pass filter is required to be less than the switching frequency and is recommended that it is approximately ten times smaller than the switching frequency. A lower cut off frequency will result in a much cleaner bus voltage but the trade off is that a much larger inductor is required as L_F increases quadratically as f_c decreases. An increased inductor size will increase both cost and size of the converter as well as a slower response time with high ripple.



(a) Capacitor bank without the snubber.



(b) Capacitor bank with the snubber.

Figure E.8: Simulated effects of the addition of the snubber showing the damping of the higher order frequencies on the bus

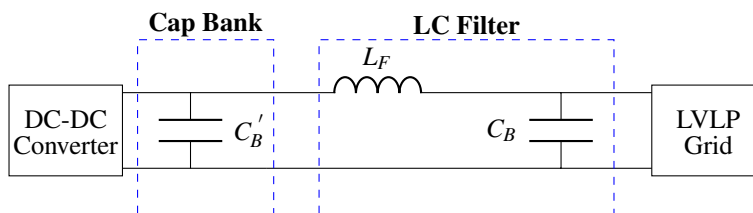


Figure E.9: Addition of LC filter to form a pi network.

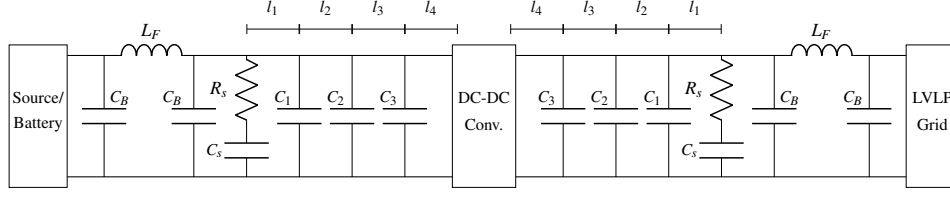


Figure E.10: Layout of the PCB where l_1, l_2, l_3, l_4 are the PCB track lengths between component terminals.

E.6 PCB Layout Considerations

Using the proposed sizing methods and transient suppression techniques careful consideration needs to be paid to the board layout as high inductance on the low ESL capacitor current path negates the suppression techniques discussed in Section E.4. The distances ($l_1 - l_4$ in Figure E.10) between the pads of the capacitor and the input/output of converter needs to be as short as possible to ensure minimal additional inductance on the suppression capacitors. It is recommended that C_3 be placed as close to the input/output as possible followed by C_2 and then by C_1 as shown in Figure E.10.

E.7 Filter Performance

In order to evaluate the performance of the filtering network the distributed LVLP DC Grid is modelled using Figure E.11. A lead acid battery is used to set the grid voltage to 12 V. Interconnecting the battery to the converter is a transmission line. Table E.1 specifies the grid and converter specification upon which the performance is tested. The values of the capacitor bank and inductor to deliver 90 W of power is presented in Table E.2. The bulk capacitor required for 90 W on a 12 V grid is $62.5 \mu\text{F}$. A $66 \mu\text{F}$ capacitor is used instead as this can be achieved using three $22 \mu\text{F}$ capacitors. The bus voltage when transferring the rated power shown in Figure E.12 and shows as a relatively clean bus which ensures that the converter is LVLP DC compatible.

Table E.1: Grid Parameters

Parameter	Value	Parameter	Value
Converter Power	90 W	f_s	50 kHz
V_G	12 V	R_{Bat}	5.46 m Ω
R_L	0.06 Ω	L_L	2.56 μ H
C_L	0.04 nF	G_L	∞
V_S	12.8 V		

Table E.2: Properties of the capacitor bank and LC filter

Parameter	Value	Parameter	Value
C_B	66 μ F	C_1	6 μ F
C_2	660 nF	C_3	66 nF
C_S	3 μ F	R_S	0.1 Ω
f_c	5 kHz	L_F	15 μ H

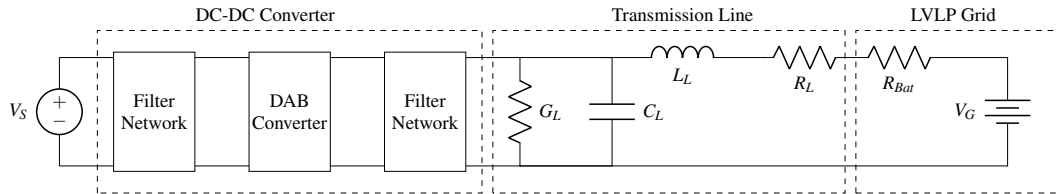


Figure E.11: Practical model for LVLP DC Grid.

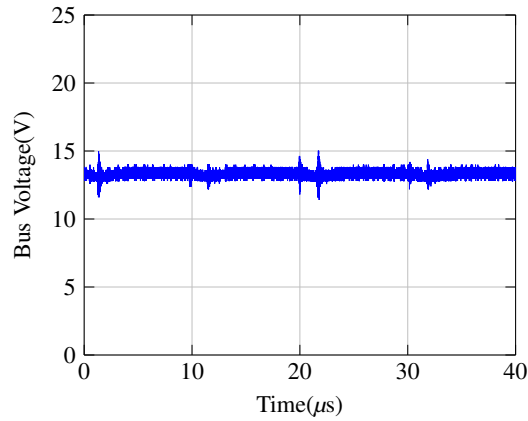


Figure E.12: Measured bus voltage using the recommended filter network at a power transfer of 89 W.

E.8 Conclusion

A design methodology was presented for designing the filter network for DC-DC converters that operate on an LVLP DC grid. The converter was able to successfully transfer 89 W of power to a 12 V LVLP grid setup using a lead acid battery. The proposed methodology allows for high current DC-DC converters to operate on LVLP Grids using the filtering networks to suppress high frequency voltage transients that arise from high current DC-DC converters. This methodology ensured that the bulk capacitor is not oversized which reduces costing. Using the filter network presented it was shown that a stable DC voltage can be obtained from these devices under high current transfer.

References

- [E1] M. Areff, W. A. Cronje, J. A. Naudé, and I. W. Hofsajer, “A simulation tool for ad hoc low voltage dc grids with decentralized control,” in *2017 IEEE Second International Conference on DC Microgrids (ICDCM)*, June 2017, pp. 371–377.
- [E2] M. Nasir, H. A. Khan, A. Hussain, L. Mateen, and N. A. Zaffar, “Solar pv based scalable dc microgrid for rural electrification in developing regions,” *IEEE Transactions on Sustainable Energy*, vol. PP, no. 99, pp. 1–1, 2017.
- [E3] M. Nasir, S. Iqbal, and H. A. Khan, “Optimal planning and design of low-voltage low-power solar dc microgrids,” *IEEE Transactions on Power Systems*, vol. PP, no. 99, pp. 1–1, 2017.
- [E4] J. Schonbergerschonberger, R. Duke, and S. D. Round, “Dc-bus signaling: A distributed control strategy for a hybrid renewable nanogrid,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, pp. 1453–1460, Oct 2006.
- [E5] J. Bryan, R. Duke, and S. Round, “Decentralized generator scheduling in a nanogrid using dc bus signaling,” in *IEEE Power Engineering Society General Meeting, 2004.*, June 2004, pp. 977–982 Vol.1.
- [E6] “Control strategies for DC networks: A systematic literature review,” *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 319–330, 2016.
- [E7] C. D., X. L., and Y. L., “DC voltage variation based autonomous control of DC microgrids,” *IEEE Transactions on Power Delivery*, vol. 28, no. 2, pp. 637–648, 2013.
- [E8] P. H. Huang, P. C. Liu, W. Xiao, and M. S. El Moursi, “A Novel Droop-Based Average Voltage Sharing Control Strategy for DC Microgrids,” *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1096–1106, 2015.

- [E9] K. Billings, *Switchmode Power Supply Handbook*, ser. McGraw-Hill Electronics Handbooks Series. McGraw-Hill Companies, Incorporated, 1999. [Online]. Available: <https://books.google.co.za/books?id=RwAmBvRzA3EC>
- [E10] P. Krein, *Elements of Power Electronics*, ser. Oxford series in electrical and computer engineering. Oxford University Press, 1998. [Online]. Available: <https://books.google.co.za/books?id=JBhkQgAACAAJ>
- [E11] N. Mohan, T. Undeland, and W. Robbins, *Power electronics: converters, applications, and design*. Wiley, 1995. [Online]. Available: <https://books.google.co.za/books?id=KbkQAQAAMAAJ>
- [E12] K. Inoue, T. Kato, M. Inoue, Y. Moriyama, and K. Nishii, “An oscillation suppression method of a dc power supply system with a constant power load and a lc filter,” in *2012 IEEE 13th Workshop on Control and Modeling for Power Electronics (COMPEL)*, June 2012, pp. 1–4.
- [E13] W. Wu, Y. Liu, H. Wang, M. Huang, and F. Blaabjerg, “Modelling and control design of a dual buck-boost ac/dc converter used in the dc nano-grid,” in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, May 2016, pp. 2187–2192.
- [E14] B. Zhao, Q. Song, W. Liu, and Y. Sun, “Overview of dual-active-bridge isolated bidirectional dc-dc converter for high-frequency-link power-conversion system,” *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4091–4106, Aug 2014.
- [E15] —, “Overview of dual-active-bridge isolated bidirectional dc-dc converter for high-frequency-link power-conversion system,” *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4091–4106, Aug 2014.
- [E16] E. A. Brink, “An investigation into the characteristics of dc bus structures in low voltage high current converters,” Master’s thesis, University of Johannesburg, 2007.
- [E17] J. Riedel, D. G. Holmes, B. P. McGrath, and C. Teixeira, “Active suppression of selected dc bus harmonics for dual active bridge dc-dc converters,” *IEEE Transactions on Power Electronics*, vol. 32, no. 11, pp. 8857–8867, Nov 2017.

Appendix F

Implementation of Control Algorithm

This Appendix was intended to contain the source code for the smart battery. However, due to the sensitive nature and pending patents, it cannot be published in this work. Should viewing of the source code be required please contact the author of the document.

Appendix G

PeCo Grid Test Bed

G.1 Introduction

This appendix presents the test bed on which the smart battery is tested. A diagrammatic representation of the testbed is shown in Figure G.1. The testbed has solar, storage and load blocks which contain the passive elements that are interfaced to the common bus at the centre of the bed. A general generation block utilises DC power supplies to provide constant generation. A photo of the constructed PeCo grid is shown in Figure G.2.

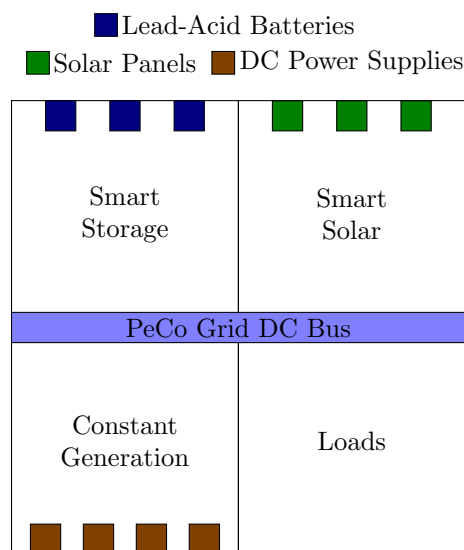


Figure G.1: Diagrammatic representation of the test bed.

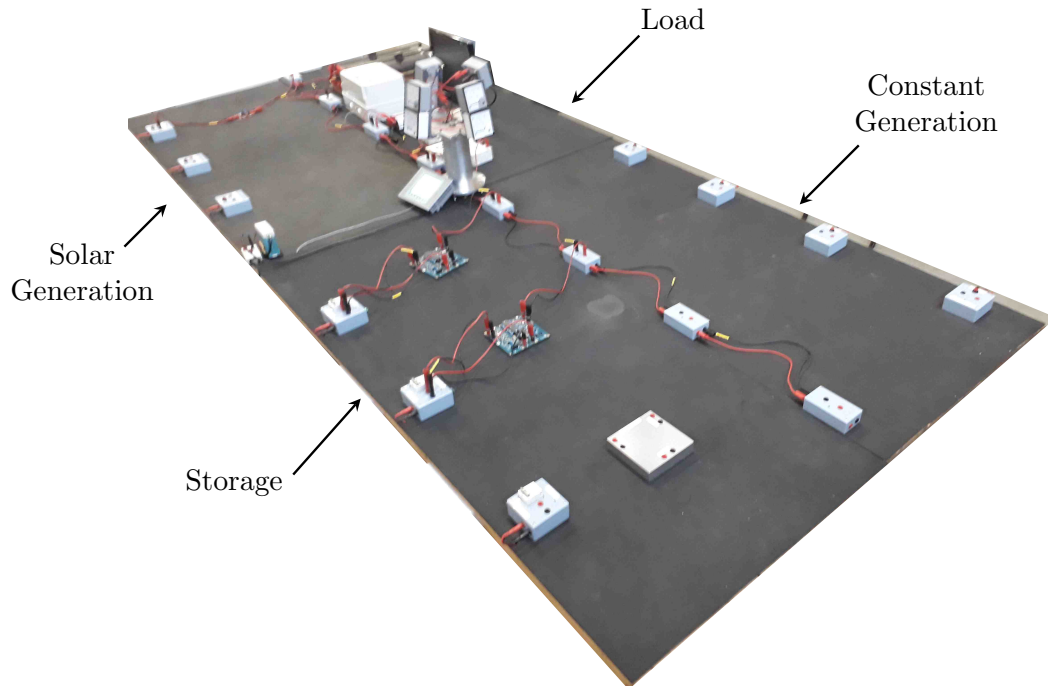


Figure G.2: Image of the constructed PeCo grid.

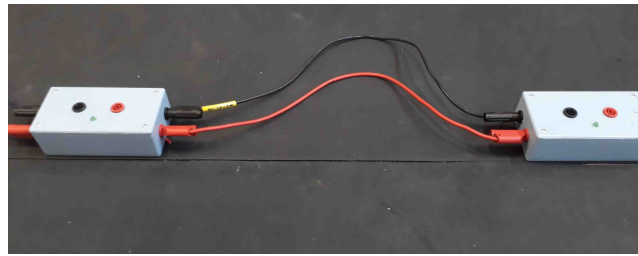


Figure G.3: Centre bus of the PeCo grid.

G.2 Centre bus and scalability

The centre bus structure is segmented using the boxes shown in Figure G.3. Smart devices plug into the common bus via the 4 mm safety sockets on each segment. The segmented bus carries advantages such as allowing different transmission lines and bus structures to be tested. The transmission cables which were used to test the smart battery in Section 7 has a DC resistance of $1.6 \Omega \cdot \text{m}^{-1}$.

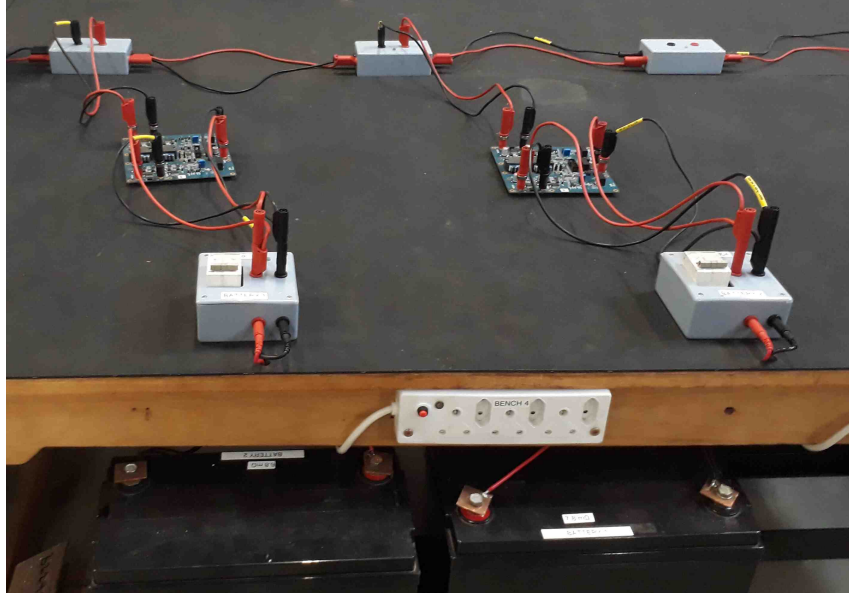


Figure G.4: Smart battery devices on the PeCo grid.

G.3 Devices on PeCo grid

The smart battery section of the PeCo grid testbed is shown in Figure G.4. The smart battery is formed by connecting a 100 Ah sealed lead-acid battery to the DAB converter. Using this combination the various devices can be powered from the smart battery. The smart battery can power devices such as those in Figure G.5. Figure G.5 shows loads that provide basic lighting, cellphone charging and television. In addition to these devices a 300 W load can also be powered off the smart batteries. Energy is generated by the smart solar device which is made up of a 30 W solar panel connected to a flyback converter.

G.4 Digital Load

A digital load is created by using the circuit shown in Figure G.6. The input impedance R_L can be varied by manipulating the input voltage V_{in} as given by equation (G.1). The amplifier circuit keeps the voltage across the fixed resistor R_A equal to the modulation voltage V_{in} . Due to this behaviour, a constant current load can be obtained as well by keeping the modulation voltage constant. The input voltage V_{in} is set using a microcontroller with a DAC converter which forms a digital

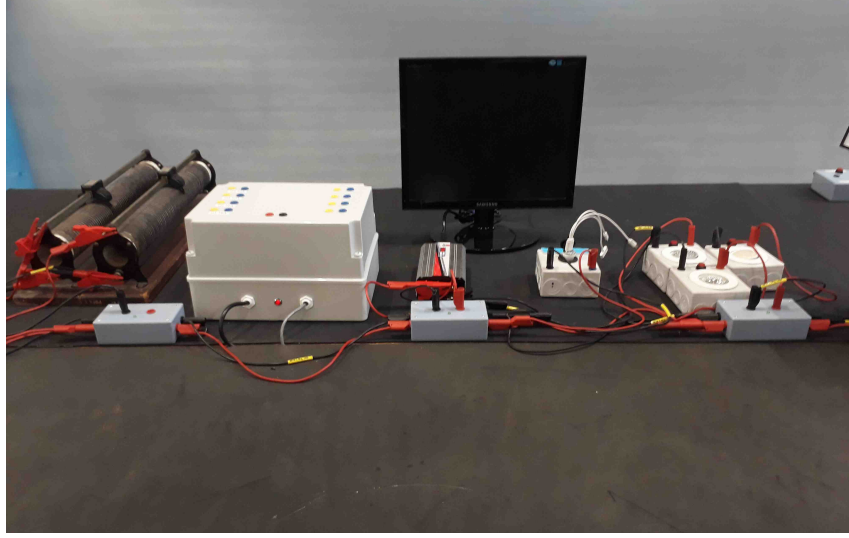


Figure G.5: Loads on the PeCo grid: 300 W resistive load, computer monitor utilising a 12 V off the shelf inverter, cellphone charger and three lights.

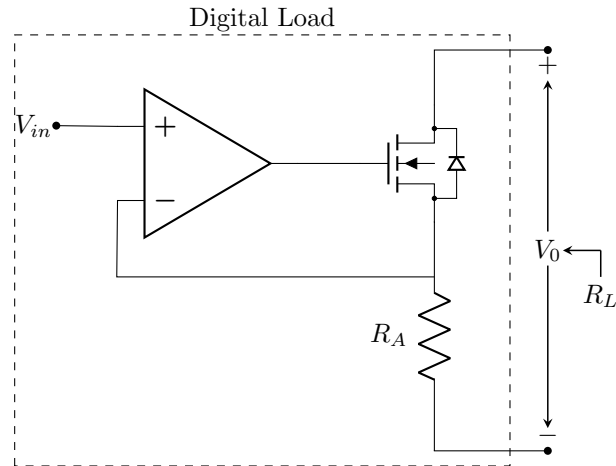


Figure G.6: Circuit diagram for the digital load.

load.

$$R_L = \frac{V_O R_A}{V_{in}} \quad (\text{G.1})$$

G.5 Conclusion

A test bed is created to test the smart battery. The given test bed allows for multiple permutations of the PeCo grid to be tested in a repeatable controllable manner. The grid permutation can be configured by simply plugging in devices to the centre bus.

Appendix H

Battery Testing

H.1 Introduction

This appendix describes the experiments carried out to observe the lead-acid batteries behaviour under loading. Two experiments were carried out to establish the behaviour. The first experiment monitors the batteries behaviour when loaded and the second experiment aims to find the relationship between the open circuit voltage and state of charge.

H.2 Battery Loading

The test setup shown in Figure H.1 uses the constant current load discussed in Appendix G to discharge the battery. The battery is discharged for three hours constantly at a rate of the 1 A. After loading the battery the switch S_L is opened and the battery is disconnected from the load. The terminal voltage behaviour during

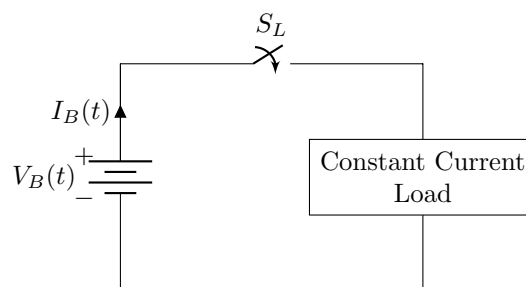


Figure H.1: Test set-up used to test the lead acid battery.

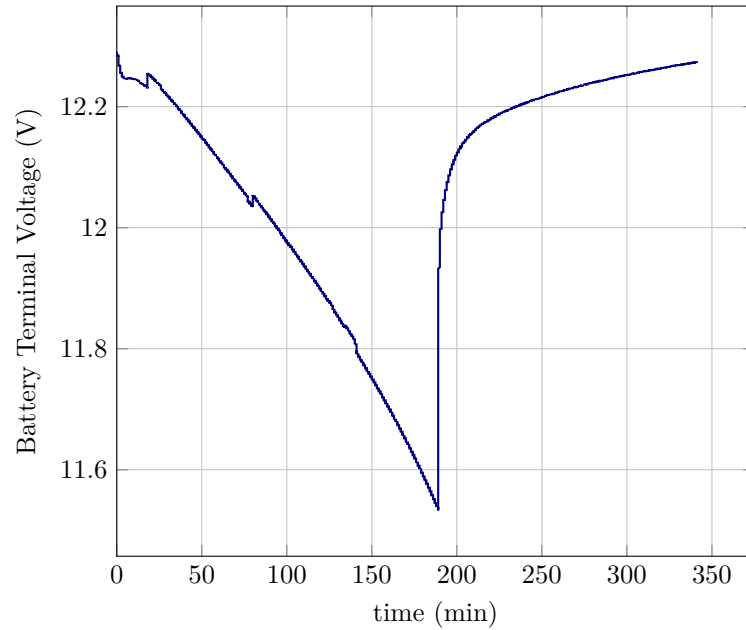


Figure H.2: Lead Acid battery discharge characteristic obtained discharging a 7 Ah RITAR RT1270 at a constant current of 1 A.

the experiment can be seen in Figure H.2 which shows the non-linear behaviour of the battery. This test shows that the battery steady state open circuit voltage is not immediately reached after disconnecting the load. The behaviour observed at 20 min and 75 min is due to the controller action of the constant current load discussed in Appendix G.

H.3 Open Circuit voltage and SOC relationship

In this experiment, the battery is discharged using a constant current load of 1 A periodically. The battery is connected to the load for an hour disconnected for two hours until the open circuit voltage stabilises. This process is continued until the battery is discharged to 80% DOD. The results from this test are shown in Figure H.3 which show the linear relationship between the SOC and stabilised open circuit voltage of the battery.

H.4 Conclusion

The lead-acid battery is a non-linear device however, the relationship between the SOC and open circuit voltage exhibits a linear behaviour. The SOC cannot be

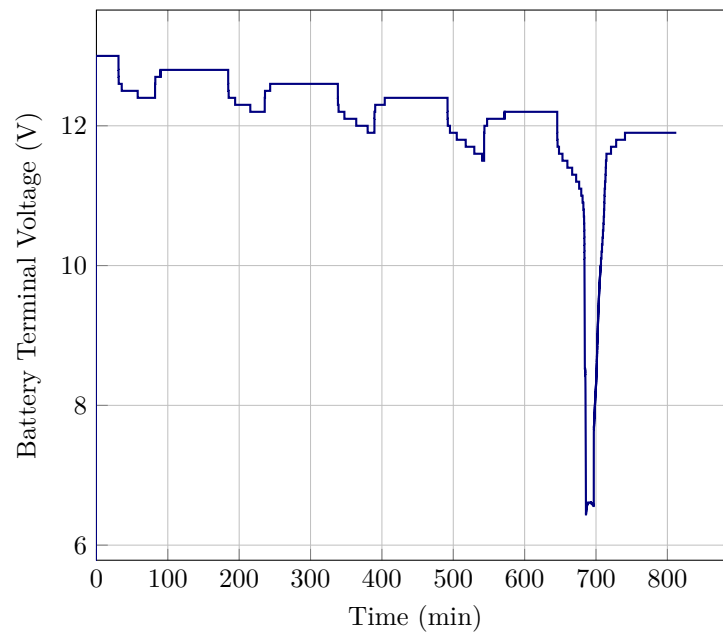


Figure H.3: Battery terminal voltage of RITAR RT1270 under constant current discharge of 1 A.

established immediately when the battery is taken offline and requires a stabilisation period.