



Faculty of Engineering

**Techno-economic Analysis of DC Microgrid and its Distributed Control
Strategies with Fault Current Mitigation Technique for Power Sharing
and Voltage Regulation**

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Techno-economic Analysis of DC Microgrid and its Distributed Control
Strategies with Fault Current Mitigation Technique for Power Sharing and
Voltage Regulation

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ABSTRACT

Recent research on DC systems revealed that DC microgrids can be an efficient, reliable and economical solution to avoid the inherent issues associated with AC power integration such as frequency control, harmonics and synchronization. One major concern of the DC microgrids with multiple converters is the control of power sharing, aiming to maintain the voltage profile, particularly during system disturbances. Under the worst scenarios, DC microgrid operation may be completely impacted if properly distributed control strategies are not considered with an effective protective approach to eliminate the fault currents. The ongoing studies presented in the area of DC microgrid control reflect its importance, however, the stability of an isolated DC microgrid in terms of power sharing and voltage regulation especially under fault conditions is not sufficiently addressed in the literature. In the first objective of this research, a framework has been proposed to assess the technical benefits of implementing either AC or DC distribution considering the existing AC infrastructure. Further, a Hybrid Optimization of Multiple Electric Renewables (HOMER) based analysis has been carried out to determine the most economical and optimal size of an isolated solar PV system with its energy storage to be connected either as an AC or DC microgrid. From the obtained outcomes of the above-mentioned framework, a distributed secondary control strategy has been developed in the second objective. This approach is based on average-voltage/average-current control and circulating current minimization for DC bus voltage regulation and maintaining power sharing under different scenarios. In that sense, an additional current feedback loop is introduced to modify the microgrid reference voltage during overload conditions to minimize the line voltage drop and distribution losses. Finally, to mitigate the vulnerability of isolated DC microgrid control due to fault conditions, a preventive scheme of controllable fault current limiter (C-FCL) has been designed in the

third objective. The C-FCL acts in a coordinated manner with the implemented control of power sharing and voltage regulation. This research study was carried out using the HOMER optimizer and MATLAB/Simulink with small-scale experimental validation. The results show that applying DC voltage magnitude equal to the peak value of AC voltage reduces the power loss of DC microgrid up to half value compared to AC microgrid and the voltage drop in the distribution lines reduces by 29.3%. It is revealed that the proposed control strategy has better voltage regulation, and power sharing performance without any significant deviation imposed by variation in PV generation as well as load switching. Further, using the proposed C-FCL protective scheme can limit the fault current magnitudes for different fault locations, keeping the converters operating in a safe mode during fault conditions. The C-FCL increases the fault clearance time for the protection system providing more efficient and reliable operation of the DC microgrid.

Keywords: DC microgrids, techno-economic analysis, power sharing, fault current limitation

Pembangunan Strategi Pengendalian Teragih dengan Teknik Mitigasi Arus Kesalahan untuk Perkongsian Daya dan Peraturan Voltan dalam DC Mikrogrid

ABSTRAK

Penyelidikan dan kemajuan terkini dalam sistem DC menunjukkan bahawa mikrogrid DC dan pengedaran DC merupakan penyelesaian yang cekap, boleh dipercayai, dan ekonomik untuk mengelakkan masalah sistem kuasa AC seperti kawalan frekuensi, harmonik dan penyegerakan. Walau bagaimanapun, satu masalah utama mikrogrid DC dengan beberapa penukar adalah kawalan perkongsian kuasa, yang bertujuan untuk mengekalkan profil voltan terutamanya semasa gangguan sistem. Di dalam senario terburuk, operasi mikrogrid DC mungkin benar-benar terjejas jika strategi kawalan terdistribusi yang betul dan pendekatan perlindungan yang berkesan untuk menghilangkan arus kerosakan tidak dipertimbangkan. Kebanyakan kajian bidang kawalan mikrogrid DC yang dijalankan mencerminkan kepentingannya, walau bagaimanapun, kestabilan mikrogrid DC dari segi pembahagian kuasa, peraturan voltan dan batasan arus kerosakan tidak diberi perhatian yang cukup dalam literatur. Dalam objektif pertama penyelidikan ini, kerangka kerja untuk menilai manfaat teknikal dan kewangan dalam melaksanakan mikrogrid AC dan DC telah dicadangkan. Selanjutnya, tingkah laku dinamik mikrogrid AC dan DC telah dianalisis ketika setiap sistem mengalami gangguan seperti kesalahan litar pintas, dengan tujuan untuk menilai tindak balas sistem. Pada tahap berikutnya, analisis ekonomi telah dilakukan untuk menentukan ukuran optimum sistem PV suria yang disambungkan ke setiap mikrogrid AC atau DC dengan simpanan tenaganya, menurut data profil meteorologi dan muatan dari daerah terpencil terpilih di Sarawak (Malaysia). Dalam objektif kedua, strategi kawalan pengedaran sekunder telah dikembangkan untuk melancarkan voltan output dan mengekalkan pembahagian daya berdasarkan kawalan voltan rata-rata / arus-arus dan

pengurangan arus yang beredar. Oleh itu, gelung maklum balas arus tambahan diperkenalkan untuk mengubah voltan rujukan mikrogrid semasa keadaan beban yang berlebihan untuk meminimumkan penurunan voltan talian dan kehilangan kuasa. Untuk mengurangkan kesan peningkatan arus yang cepat pada pembahagian kuasa dan kawalan peraturan voltan semasa keadaan kerosakan, skema pencegahan pembatas arus kerosakan yang dapat dikawal (C-FCL) telah dirancang pada objektif ketiga dan diuji menggunakan konfigurasi mikrogrid cincin DC. C-FCL bertindak secara terkoordinasi dengan pelaksanaan algoritma pembahagian kuasa dan peraturan voltan. Kajian di atas dilakukan dengan menggunakan HOMER dan MATLAB / Simulink. Hasilnya menunjukkan bahawa penerapan voltan DC yang sama dengan nilai puncak bentuk gelombang AC boleh mengurangkan kehilangan kuasa mikrogrid DC hingga separuh nilai berbanding dengan mikrogrid AC dan penurunan pengedaran voltan berkurang sebanyak 29.3%. Ini menunjukkan bahawa strategi pengendalian yang dicadangkan mempunyai peraturan voltan dan prestasi perkongsian daya yang lebih baik di dalam semua kondisi beban. Di samping itu, C-FCL yang dicadangkan efektif dalam membatasi magnitud arus kesalahan di lokasi yang berlainan untuk mengurangkan kerentanan kawalan mikrogrid terhadap kesalahan sementara. Akhirnya, hasil yang diperoleh mengesahkan bahawa strategi kawalan yang dicadangkan dengan skema pencegahan arus kesalahan yang diselaraskan memberikan operasi mikrogrid DC yang lebih cekap dan boleh dipercayai.

Kata kunci: *Mikrogrid DC, analisis tekno-ekonomi, perkongsian kuasa, had arus kesalahan*

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LIST OF ABBREVIATIONS

CCT	Critical Clearing Time
CERTS	Electric Reliability Technology Solutions
C-FCL	Controllable Fault Current Limiter
COE	Cost of Energy
CRF	Capital Recovery Factor
DG	Distributed Generation
DRES	Distributed Renewable Energy Sources
DRG	Distributed Renewable Generation
ESS	Energy Storage Systems
FCL	Fault current limiter
HOMER	Hybrid Optimization Model for Electric Renewable
HVDC	High-Voltage DC
LVDC	Low-Voltage DC
MTDC	Multi-Terminal DC
NPC	Net Present Cost
PCC	Point of Common Coupling
PQ	Power quality
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
SAA	Scaled Annual Average

CHAPTER 1

INTRODUCTION

1.1 Study Background

According to the ‘Energy trends: What’s the outlook for 2035’ report [1], global energy demand is expected to grow by nearly 40% of that in 2015. Most of the increase in energy demand is foreseen in the fast-growing and developing economies. The global energy demand in past decades was supplied by fossil fuels, however, due to price fluctuations, limited natural resources and the impact of CO₂ emissions, the focus on developing renewable energies as alternatives to fossil fuels has grown rapidly throughout the world. The main reason behind this is the rapid growth of competitive supply markets and developments of low-cost, low-power distributed generation (DG) technologies compared to the high cost of transmission and distribution networks especially in rural and remote areas with low power demands. Distributed Renewable Generation (DRG) plays a key role in providing services such as electrification, modern communication to facilitate education, improved health and other socio-economic activities with co-benefits such as reducing air pollution and positive effects on income growth in rural areas where utility grid supply is difficult and expensive [2].

Globally, an approximate 6.5% annual growth in renewable energy production is expected over the next 20 years. The share of renewable energy sources (RES) in primary energy production is expected to grow from 3% in 2015 to 8% by the end of 2035. During the past decades, approximately 145 countries adopted policies that support renewable energy technologies. At the present stage, 10 Terawatts (TW) of electrical power is consumed throughout the world annually, and this consumption is expected to reach 30 TW

by 2050. Global climate reports indicate that greenhouse gas emissions must be reduced to 80% of their 1990 levels to prevent global warming. Therefore, 20 TW of clean, renewable energy is required to level out the hazardous gases in the atmosphere [1], [3], [4].

The largest growth in renewable power generation capacity, 178 Gigawatt (GW), was recorded in 2017, comprising almost 70% of the net additions to worldwide renewable power generating capacity for the year. Meanwhile, total global renewable power capacity reached 2,195 GW. Approximately 10.3 million people were employed (directly and indirectly) by the renewable energy sector, and new investments of approximately US\$280 billion were made globally. Strong growth in renewable energy was observed in the power sector. However, current advances are uneven across sectors, such as transportation, heating and cooling, which comprise approximately 80% of net global energy demand, because policymakers focused on providing electricity access, especially in remote and rural areas [5]. Solar photovoltaic (PV) and wind power capacity installations account for approximately 56% and 29% of energy generation, respectively, while small hydropower, below 50 megawatts, contributed 11% of renewable power capacity added in 2017. Figure 1.1 (a) shows the percentage of RES participation in total global renewable power generation capacity at the end of 2017, while (b) shows the participation of new installations in 2017. Figure 1.1(b) indicates that solar PV and wind power installations were remarkable in the power sector. Therefore, future research targeted these sources. Nearly 99 GW of solar power was added globally, and total solar capacity worldwide increased to 402 GW.

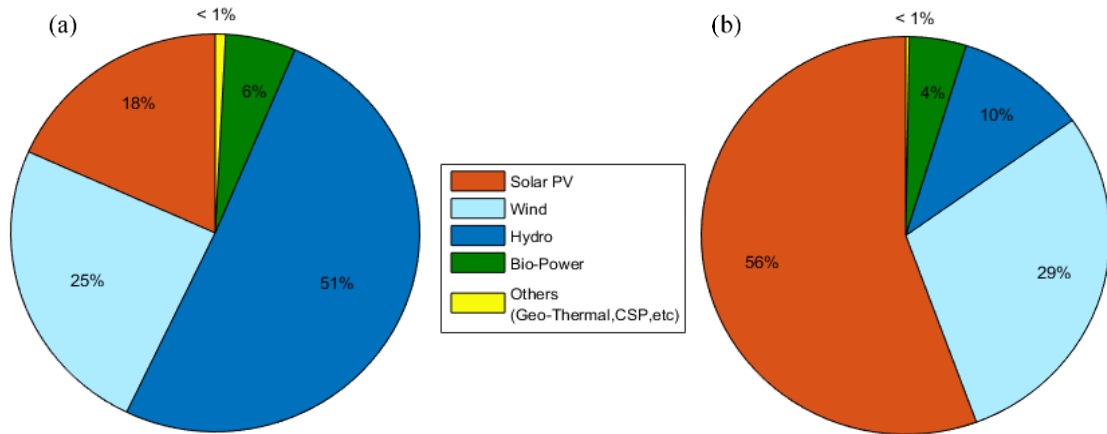


Figure 1.1: Total Installed Renewable Power Capacity Worldwide (a) At the end of 2017; (b) New Installation in 2017 [5]

Asian markets continue to dominate solar power addition for the fifth consecutive year, with China holding the first position in the top 10 rankings for solar power addition, followed by the United States, India, Japan, Turkey, Germany, Australia, South Korea, United Kingdom and Brazil [5], [6]. Table 1.1 shows the top-ranked countries in total and added solar power capacities at the end of 2017.

Table 1.1: Top10 Countries for Solar Power Capacity Installation in 2017 [5], [6]

No	Total Solar Power Generating Capacity Installed in GW at the end of 2017		The Newly Installed Solar Power Generating Capacity (GW) in 2017	
1	China	131	China	53
2	USA	51	USA	10.6
3	Japan	49	India	9.1
4	Germany	42	Japan	7

Table 1.1 continued

5	Italy	19.7	Turkey	2.6
6	India	18.3	Germany	1.8
7	United Kingdom	12.7	Australia	1.25
8	France	8	South Korea	1.2
9	Australia	7.2	United Kingdom	0.9
10	Spain	5.6	Brazil	0.9
	Total solar power capacity worldwide	402	Total added solar power capacity in 2017	99

Wind power generation has also become a clean option in an increasing number of markets worldwide. The cumulative worldwide installed wind power generation capacity at the end of 2017 was 539 GW. The global wind power growth observed over the last five years is as follows: 52 GW in 2017, 54.64 GW in 2016, 63.33 GW in 2015, 51.68 GW in 2014 and 36.02 GW in 2013. Commercial wind activity was observed in more than 80 countries, while 26 countries generated more than 1 GW of wind power. Asian countries (China, India and Japan) were the largest markets for wind power capacity installation in 2017, accounting for approximately 47% of total new capacity installations worldwide, followed by the European Union with 32% and North America with 15%. At the end of 2017, China led the world in both total and added wind power capacity (188.23 GW), leaving the United States behind (89.08 GW). The top 10 countries in total wind energy generation capacity were Germany, India, Spain, the United Kingdom, France, Brazil, Canada and Italy. The top 10 countries in capacity addition in 2017 were China, the United States, Germany,

India, United Kingdom, Brazil, France, Canada, Italy and Spain [5], [6]. Table 1.2 summarizes the total and added wind power capacity data from the top 10 countries at the end of 2017.

Table 1.2: Top10 Countries for Wind Power Capacity Installations in 2017 [5], [6]

No	Total Wind Power Generation Capacity at the end of 2017 in GW		The Newly Installations of Wind Power Generation (GW) in 2017	
1	China	188.23	China	19.54
2	United States	89.08	United States	6.90
3	Germany	56.13	Germany	6.11
4	India	32.85	India	4.18
5	Spain	23.17	United Kingdom	3.84
6	United Kingdom	18.87	Brazil	2.02
7	France	13.76	France	1.69
8	Brazil	12.76	South Africa	0.62
9	Canada	12.24	Poland	0.61
10	Italy	9.48	Finland	0.57
	Total wind power capacity worldwide	539	Wind power capacity additions in 2017	52

1.2 Microgrid Concept

Although utility grid propagation or extension is the first option for electrification and should be economical when compared to other off-grid options, however, it is a

challenge to integrate distributed renewable energy sources (DRES) such as PV systems, wind turbines, fuel cells, micro-hydro and energy storage systems (ESS) directly into the utility grids because of their intermittence and uncertainty. The cost of supplying grid-based electricity to remote areas with low power demands becomes uneconomical, in such situations, stand-alone renewable energy microgrids based on smart metering and control become the most viable option for sustainable development. In 1999, the Consortium for Electric Reliability Technology Solutions (CERTS) originated the concept of the modern grid-connected microgrid system. CERTS define a microgrid as a localized group of controllable DRES and loads that present itself as a single customer or a small generator to the existing utility grid, which can disconnect and independently operate according to the physical and/or economic conditions. The microgrid concept has proven itself as one of the most practical solutions to utilize DRES and can eliminate the perceived challenges of integration with improved reliability in the case of natural disasters, physical/cyber-attacks, and cascading power failures with decentralized and autonomous control solutions [7]. However, all these benefits are dependent on efficient coordination within the microgrid as well as with the utility grid. Any discoordination can lead to critical problems such as islanding and protection issues. Therefore, the intelligent power grid/smart grid with real-time monitoring and optimization needs to be developed to ensure a more reliable power delivery to the end-user. The smart grid concept integrates communication networks with power systems to provide real-time monitoring (smart metering) and control of power system components. According to the US National Institute of Standards and Technology (NIST), a smart grid is defined as “a transition process from the existing power system to the future Information and Communication Technologies (ICT) based power system”. A smart grid is capable of bidirectional power flow and has full control over the grid components using

advanced digital communication infrastructures for intelligent remote monitoring/sensing, metering, and control. An ideal concept of a smart microgrid network is shown in Figure 1.2.

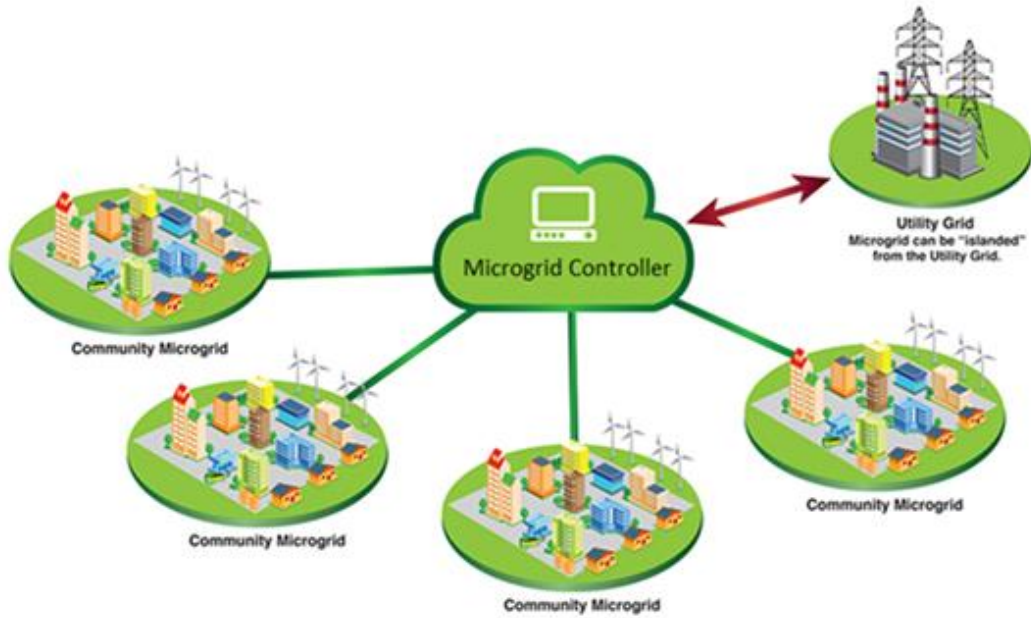


Figure 1.2: Future Smart Microgrid Network [9]

In addition, the smart grid concept also allows consumers to have full control and management of their power consumption and production (if the consumer holds a power source), while utility companies can implement advanced services such as load shifting and peak shaving for efficient energy usage and cost optimization. Smart metering and advanced sensors based on real-time communication are the key elements of smart grid technologies that enable the smart grid to operate in an automated fashion [7]–[9]. The defining features that distinguish smart microgrids from the existing grids are listed in Table 1.3.

Table 1.3: Comparison of Existing Grids and Smart Microgrids [7]-[9]

Features	Existing Grid	Smart Microgrid
Type of system	Electromechanical	Digital
Generation	Centralized	Distributed
Power flow	Uni-directional	Bi-directional
Communication	One-Way	Two-Way
Control	Limited	Pervasive
Structure	Hierarchical	Network
Sensors	Few	Throughout
Restoration	Manual	Self-Healing
Checking/Testing	Manual	Remote
Customer Choices	Few	Many

The Global Smart Grid Federation (GSGF) focuses on smart grids (both grid-connected and islanded) to minimize the effect of DRES on the utility grid. Based on the results from existing smart grid pilot projects around the world, GSGF identifies various functions including demand response, ancillary services, electricity bill reduction, barriers, and solutions for promoting smart grid commercialization. It has been perceived by GSGF that cost reduction of microgrid technologies and changes in the regulatory framework will enable smart microgrids to shift from pilot projects to commercial deployment [10].

Microgrids can be AC or DC depending upon the voltage type at the common bus. Further, it may be grid-connected i.e., a part of the distribution system or may operate as an isolated power system (stand-alone/islanded mode), composed of RES, engine generator, ESS, and loads. The interconnecting point of a microgrid with the main power grid is known

as the point of common coupling (PCC). Stand-alone microgrid is considered a viable solution for electrification in small remote areas. Stand-alone microgrid can be implemented with AC or DC distribution networks. A general concept of AC and DC microgrids is shown in Figure 1.3.

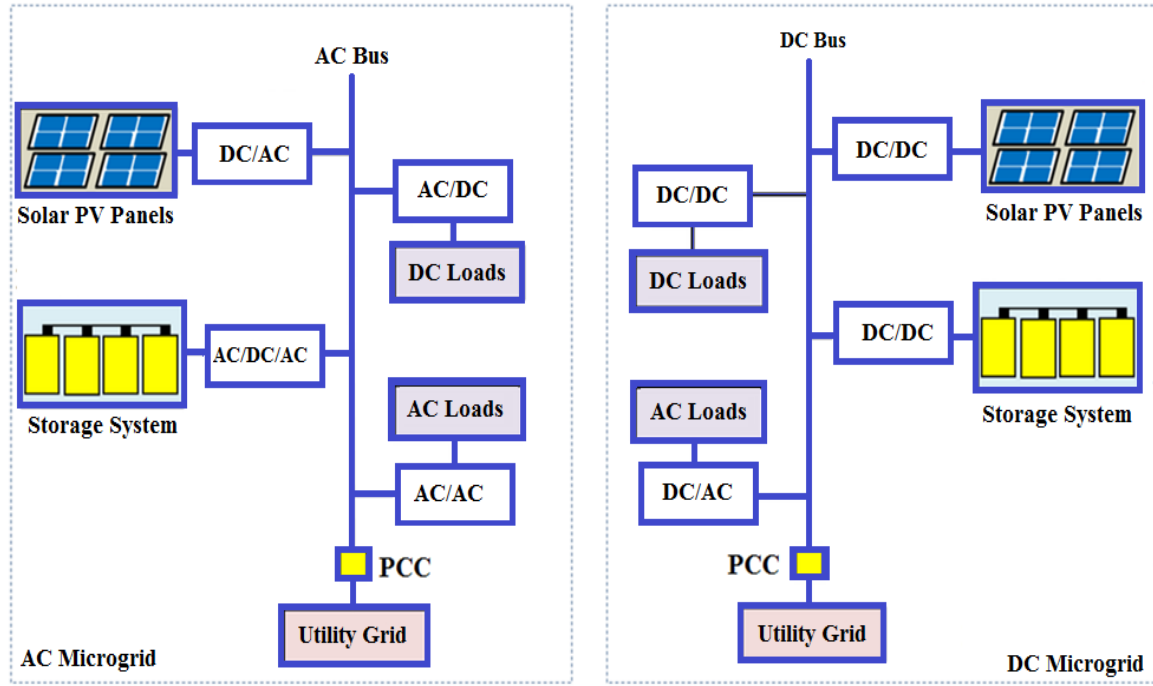


Figure 1.3: Structures of AC and DC Microgrid [12]

The idea of DC microgrid appeared soon after the concept of microgrid was proposed. DC microgrids have been gaining continually increasing interest over the past years both in academia and industry. It is commonly designed for connecting distributed RES, ESS and DC loads. This is because many RES, such as PV systems, fuel cells, wind generators, and ESS, produce DC power and normally have DC links at their interface converter stages [11], [12].

1.3 Rural Electrification in Sarawak

Malaysia, although moving rapidly towards being a developed nation, has a considerable number of under-developed rural areas. Most of these are tiny pockets of

inhabited villages, sprawling over large areas of Sabah and Sarawak (the Borneo Island). In Sarawak, there are cases where high tension electricity wires from a large hydroelectric plant pass through remote villages but the cost of stepping down the voltage levels to serve these tiny communities is economically not feasible. Therefore, local authorities usually resort to temporary measures such as installing small diesel-powered generators and solar panels in some accessible remote villages. However, diesel generators are found to be expensive to operate for long durations. Also, fuel transportation to remote communities of Sarawak becomes much difficult. Remote people of Sarawak are normally settled in small villages comprised of around 20–40 families. A few bigger villages of up to 200 families can also be found. Some well-established villages do have free basic amenities such as health clinics and schools provided by the government. Using the fuel and operating funds provided by the government, government-owned amenities in the villages are normally well electrified using standalone diesel generators and solar energy systems. In Sarawak, diesel generators are distributed to villages in a one-off mini rural project (MRP) [13]. Also, the Sarawak Alternative Rural Electrification Scheme (SARES) was launched in 2016 to speed up efforts towards full electricity coverage in the state by utilizing renewables like solar and micro-hydro in Sarawak's interior. This integrated initiative of the State Government, supported by Sarawak Energy Berhad (SEB), aims to provide 24-hour electricity supply through advancements in alternative energy technology to remote communities where it is very difficult and will take significant amount of time to connect to the main electricity grid. Some 400 villages in the remote rural heartlands of Sarawak are impossible to connect to the main electricity grid. The extremely rugged and challenging terrain means these communities cannot be supplied with electricity by extending distribution network. However, this

logistical challenge is not stopping the state government from fulfilling its commitment to provide electricity to each and every Sarawakian where possible [14].

With the advancements in alternative renewable technologies, there are more possibilities in applications for stand-alone off-grid supply. About 2,000 households located in remote areas such as Batang Ai, the Murum Resettlement Scheme in Belaga, Pelagus and Katibas in Central Region, Baram, Bario and Ba' Kelalan in the north are already connected with 24-hour electricity through such off-grid alternative technology funded by the government or by corporate social responsibility (CSR) program initiated by SEB. But still over 8,700 households in the 300 isolated villages are without 24-hour supply, dependent on noisy and expensive diesel generators which typically supply only a few hours of power after nightfall. The State Government headed by the Chief Minister's Office, together with Sarawak Energy and the Public Works Department, is embarking on a bold integrated effort to power up these villages utilizing renewable sources like solar photovoltaic systems with energy storage and back-up diesel generators and micro-hydro, where available [14].

1.4 Problem Statement

To minimize overall cost and ensure reliable operation of microgrids, techno-economic feasibility, optimal configuration, and sizing of renewable power sources as well as energy storage devices are highly important. Some basic parameters to be considered are the net present capital cost, operation and maintenance (O&M) cost, energy efficiency, voltage magnitudes and network configuration [15].

The main control objective of DC microgrid operation is to ensure a stable bus voltage and proper load current sharing among the power sources, irrespective of load or source power variations. Droop control is commonly used in DC microgrids to achieve load

current sharing; however, a voltage deviation is imposed by the droop resistances (used for current sharing) on the common DC bus voltage and the output voltage is linearly reduced with increasing output current. As a result, there is a trade-off between voltage regulation and current sharing accuracy. Unbalanced voltage regulation and improper current sharing between power converters of different power capacities generate circulating currents in the system [16]–[18]. Further, the low inertia of RES and non-zero crossing nature of DC voltages, DC microgrids, fed by RES only, are more vulnerable to transients and faults. The high magnitude of fault currents can destabilize the overall microgrid control as well as require robust protective devices of higher ratings. On the other hand, the constant power behavior of power converters acts as loads and adds a nonlinear effect that makes system control unstable [19].

In a stand-alone DC microgrid, fault currents are supplied only by DC-DC power converters and limited by the power rating of these converters. As a result, the IGBTs in power converters are blocked for self-protection and the overall microgrid control is lost [20]–[22]. Hence, the output current of DC-DC converters should be limited within the rated capacity to mitigate the vulnerability of DC microgrid control against transient faults and system disturbances.

1.5 Motivation

In the last decade, the renewed interest shown in power generation from DRES has been mainly motivated by advances in generation technologies that have made smaller, viable and feasible renewable power generating units, along with the limitations of fossil fuels and an increasing awareness of environmental issues. The penetration level of distributed generation units is increasing, and it is expected that this growth will continue

over the years to come. This thesis is motivated by the rapid growth of distributed generation from RES and the challenges associated with integration, control, and energy efficiency. The key motivations are highlighted below.

- i. Feasibility and advantages of DC microgrids and low-voltage DC systems in comparison to their AC counterparts.
- ii. Optimal microgrid configuration to fulfill the required energy demand in a cost-effective manner.
- iii. Stable and reliable DC microgrid system for remote areas, capable to cope with the variable power generation from RES and consumption.
- iv. In the absence of rotating inertia, resiliency of DC microgrid control against transient disturbances and faults is an important research issue and needs to be addressed.

1.6 Research Questions

This research aims to find out some key issues and solutions that hinder the practical applications of DC microgrids and DC distribution systems. The research questions are:

- i. What are the key technical issues that influence and empower the use of DC systems while utilizing DRES?
- ii. How a stable output voltage and proportional power sharing can be achieved simultaneously among multiple converters of different power ratings in a DC microgrid?

- iii. How the damping performance of the DC microgrid control system can be improved to mitigate the vulnerability of the DC microgrid against system disturbances and transient faults?

1.7 Hypothesis

Recent developments and integration of RES in the traditional utility grids have raised many technical problems as this power fluctuates with the variable nature of RES. Further, the load in power systems is considered to be a continuous variable, hence, it becomes a major challenge to deliver power according to the load requirements. The first hypothesis of this study is that if RES based DC microgrids offer reduced overall cost of energy with improved energy efficiency, then low-voltage DC (LVDC) distribution using the existing AC network should be feasible both technically and economically.

DC microgrids and DC distribution systems allow higher accommodation of RES. However, if multiple DC microgrids are sharing power as an isolated power network then proper load power sharing among different RES and voltage regulation issues needs to be solved by developing advanced control algorithms. The control algorithm should be reliable to perform efficiently during different load conditions.

Furthermore, isolated DC microgrids are more vulnerable to transient disturbances and faults. Excessive output current from DC-DC converters can switch the power converters into self-protection mode before the operation of protective devices. If a DC microgrid is subjected to transient disturbances and faults, then the higher magnitudes of fault currents should be limited quickly using robust and intelligent current limiting techniques to mitigate the vulnerability of DC microgrid control.

1.8 Research Objectives

The research questions in Section 1.6 can be achieved through the following set of objectives:

- i. To investigate the inherent issues associated with the integration of DRES and perform the techno-economic feasibility as well as the optimal configuration of DC microgrid using existing AC infrastructure;
- ii. To develop an efficient distributed control strategy for power sharing and voltage regulation by power converters under different load conditions; and
- iii. To mitigate the vulnerability of DC microgrid control against transient faults by limiting the output current of power converters.

1.9 Scope of Study

First, this study provides insight to identify the key challenges in the deployment of off-grid solar PV systems for the electrification of remote communities in Sarawak. A framework is proposed to find out the optimal configuration and evaluate the technical and financial benefits of implementing AC and DC microgrids. In this context, a remote area of Bario (Sarawak) was selected as a target location to obtain meteorological data and calculate microgrid components. The analysis of dynamic behaviors of AC and DC microgrids, when each system is subjected to disturbance such as short-circuit fault has been presented, aiming to evaluate the system response. In the next stage, a distributed control strategy has been developed for voltage regulation and power sharing, considering the variable nature of RES and changing load demands. The developed control strategy is capable to minimize the voltage drop and reduce the line losses during overload conditions. Finally, a fault current

limiting scheme has been presented to mitigate the vulnerability of DC microgrid control against transient faults and enhance the damping capability of DC microgrid.

A real experiment for the DC microgrid Simulink model in a laboratory environment is not possible to implement as it needs a huge integrated generating system with three buses. Further, the DC grid in a smaller size that can be installed and tested with the currently available facilities is not practically manageable. Simulating a real fault condition for any system with higher power levels in the laboratory is not possible due to health and safety issues and restrictions. Hence an alternative approach has been employed by structuring a simple experimental setup as proof of concept to demonstrate the basic applied idea of power sharing and verify the proposed controlling scheme designed in MATLAB Simulink environment. Due to the lack of in-depth techno-economic assessment that has the potential to enhance the execution requirements of DC microgrids and the shortage in similar studies or similar objectives as proposed in this thesis, the performance of the DC microgrid in some particular cases has been benchmarked by comparing it with the AC microgrid as it has common standards and regulations. Investigation of cable properties is out of the scope of this thesis. In the case of low voltage and low power networks, capacitance and inductance can be neglected. This assumption was made to simplify the technical comparison as these factors are dependent on frequency which is zero for DC systems. The referred standard IEC 61089 describes the Ohmic impedance of overhead distribution conductors which has been used for calculation in this study.

1.10 Thesis Organization

This thesis first introduces the worldwide expansion of electrical power generation from RES by presenting recent statistical data, AC and DC microgrid concepts with some

practically deployed examples and an idea of rural and remote electrification in Sarawak, Malaysia.

The literature review chapter first discusses some key inherent issues associated with the integration of distributed power generated from RES, their possible solutions and the DC microgrid concept for efficient integration. A detailed comparison of AC and DC microgrids and the available standards for DC microgrids are also presented for better understanding. Further, different methods of DC microgrid control available in the literature are reviewed and analyzed to identify the research gap.

A framework to find out the optimal configuration and evaluate the techno-economic feasibility of implementing AC and DC microgrids using existing AC infrastructure is presented in chapter 3. A remote area of Bario, Sarawak was identified to obtain the meteorological data and calculate the microgrid components. The analysis of dynamic behaviors of AC and DC microgrids, when each system is subjected to disturbance such as short-circuit fault, has been presented, aiming to evaluate the system response.

In chapter 4, a distributed control strategy has been developed for simultaneous voltage regulation and power sharing control between different solar power sources, considering the variable nature of solar power and changing load demands. The developed control strategy is capable of minimizing the voltage drop and reduce the line losses during overload conditions.

Chapter 5 presents an intelligent fault current limiting scheme to mitigate the vulnerability of DC microgrid control against transient faults and enhance the damping capability of DC microgrid. The proposed protective scheme limits the fast-rising fault

currents to avoid the self-protection mode of power converters due to excessive output current.

Finally, the studies and obtained results are concluded in chapter 6. The key challenges that hinder the deployment of DC microgrids and DC distribution as well as key future research areas are highlighted in chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, DRG integration issues along with their possible solutions documented in literature are highlighted. In addition, a comparison of AC and DC microgrid, DC microgrid standards, and its different architectures are reviewed to find out the feasibility of DC microgrid deployments. The key challenges of simultaneous power sharing control and voltage regulation in DC microgrids and different control techniques presented in the literature are evaluated and discussed. Finally, the impact of faults, fault current limitation in DC systems and protection in DC microgrids are summarized to highlight the research gap.

2.2 Distributed Renewable Generation

Distributed renewable generation (DRG) is electrical power generation from a variety of renewable energy sources (such as solar PV, wind turbines, biomass, etc.) and energy storage systems, located close to the load they serve. By contrast, DRG systems are usually decentralized and may serve as a small, isolated power system or it may be a part of the utility power system (a microgrid) [15].

The empirical studies indicate that interconnecting DRG with the distribution network is more economical than expanding transmission and distribution facilities in remote areas. In addition, instability in fossil fuels and electricity prices have fostered small residential and commercial consumers to generate their own power from RES and feed extra power to the power grid [6], [15]. The general representation of DRG is shown in Figure 2.1.

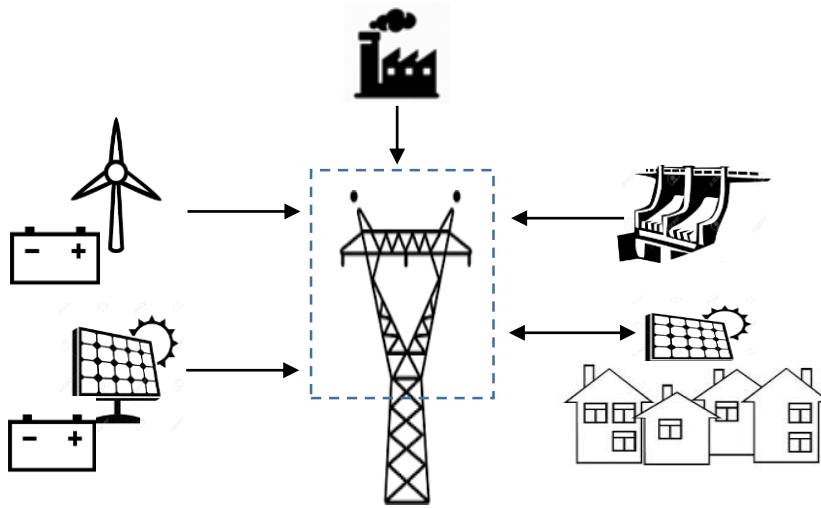


Figure 2.1: Distributed Renewable Generation

2.3 Impact of DRG on Power System

The integration of DRG with the utility grid provides a number of advantages such as energy efficiency, diversification of power sources, and improved reliability, however, inappropriate installation of DRG can lead to critical problems. The common issues include voltage instability, frequency deviation, active and reactive power imbalance and so on. The key factors behind the negative impacts of DRG are the optimal placement, proper sizing, and type of DRG technology [18].

To address the negative impacts of DRG on power systems, various characteristics of each DRG unit should be thoroughly analysed for efficient integration. These characteristics include economic, operational and dynamic characteristics of RES. The key indicators used for characterizing an RES are variability, intermittency, predictability and dispatchability [23]. The output power of solar PV generators follows the change in solar irradiance as well as is affected by other meteorological parameters such as ambient temperature and humidity, hence, solar sources are characterized by the same properties. In the case of wind power generation, wind generators are highly dependent on the wind speed

profile of a particular area. Due to the variable and intermittent nature of RES, power flow control and economic dispatch become the main challenges when integrating large-scale RES. Therefore, an appropriate energy mix should be managed to supply the power system demand [23].

To cope with the grid integration issues, different organizations and countries have set up standards and codes for interconnection on international and regional levels. Some of the recommended standards which comprehensively cover DRG requirements include IEEE 2030, IEEE 929 (being replaced by IEEE 1547), IEEE 519-1992 (revised IEEE 519-2014), IEC 61727, IEC 62109, the European standard EN 50438 and the German standards VDE-AR-N 4105: 2011 (for low voltage) and BDEW-2008 (for medium/high voltage). These standards are necessary for the integration of DRG as without their application, DRG may cause a number of technical and non-technical impacts on utility grids both in the long term and short term. The common issues include scheduling and dispatch, ancillary services requirements, synchronization, frequency/voltage regulation, power quality, stability and protection, reverse power flow, islanding protection, increased reactive power, etc. [24], [25].

Several research studies [24]–[48] were carried out to investigate the impact of DRG on the power grid. Table 2.1 demonstrates the challenges that can be faced during the integration of DRG with the power grid. The definition of each challenge with the associated effect on the power system, including the possible solution is summarized in the same table. Some key impacts are elaborated in the next subsections.

Table 2.1: Summary of Impacts of DRG on the Power Grid

Challenge	Definition	Effects on Power System	Possible Solution
Planning, Scheduling and Unit commitment [26], [28]	Coordination and unit commitment of the available generating and transmission units	Variable RES (wind and Solar) can change the operation of utility units	A time scaled advanced weather forecasting from day-ahead to real-time
Ancillary services [30], [31]	Ramp services and functions (spinning reserves) to support and facilitate the continuous flow of electrical power to continually meet the demand	Absence of ancillary services may lead to the unmatched demand-supply situation	Diesel generators, Energy storage systems (ESS), variable renewable itself
Synchronization [32], [33]	Same phase sequence/angles of 3-phases and frequency matching	Power system disturbances, power losses, phase unbalance, harmonics, voltage fluctuations	Zero-crossing detector, Phase Locked Loop (PLL), Unbalanced Harmonic based PLL, Synchronous reference frame PLL (SRFPLL),

Table 2.1 continued

Frequency and Voltage Regulation [35]-[37]	To maintain power system voltage and frequency variations in a given range	Unbalanced supply and demand for both active and reactive power	H-infinity controller, Static Compensator, automatic voltage regulator (AVR), on-line tap-changers (OLTC), Dynamic Voltage Restorer (DVR).
System Stability and protection [35]-[38]	Ability to return to its normal conditions after any disturbance	Sustained oscillations and imbalance. Protection failure	Fact devices with artificial intelligence
Power Quality [44]-[49]	Electrical bounds/limits that allow a device to function in its intended manner without significant loss of performance	Voltage sag/swell, flickers, transients, harmonics, voltage interruptions, phase unbalance, power factor, frequency deviation, etc.	Active, passive and hybrid filters, unified power quality conditioner (UPQC), Fact devices such as a static VAR compensator (SVC), DVR, Thyristor Switched Capacitor (TSC), static compensator (STATCOM)

2.3.1 Planning and Scheduling

Due to the intermittent nature of RES, the changing output of such power plants significantly impacts the operation of the power grid. Therefore, proper planning, weather forecasting, and scheduling of DRG should be carried out to meet the load characteristics in active distribution networks. Both short-term and long-term load forecasting is a prerequisite for power generation and operation. Besides the accurate load prediction problem, the power generation from both off-grid and grid-connected DRG systems is subjected to weather variations and has a more random nature, which makes it more difficult to run appropriate units for a short-term load variation. Errors in renewable power (solar irradiance or wind speed) or load forecasting may result in uncertainties for real-time microgrid operations [46], [49]–[51].

2.3.2 Ancillary Services

The power distribution grid has to compensate for power variations of PV and wind sources by adjusting the output power frequently to handle such fluctuations. Suppose a 1Megawatt PV system is covered by the clouds for 10 seconds, extra power generation at a rate of 1Megawatt per 10 seconds will be required to cope with and limit the voltage and frequency variations. Large-scale integration of intermittent RES requires a more flexible power grid to cope with the energy curtailment by deploying ESS. The amount of curtailed energy is the function of PV and wind generation patterns and the capacity of ESS deployed. However, large-scale ESS are considered uneconomical due to their high costs and energy conversion losses [52], [53]. Economic deployment of energy storage technologies has great importance to the provision of high share of RES [30].

A study in [31] was conducted for an isolated Electricity Reliability Council of Texas grid to investigate the amount of curtailed energy with RES penetration level up to 55%. In this study, 6 years' data of load patterns, solar, and wind generation profiles were used to scale out 55% RES generation scenario for a total demand of 479-Terawatt hours (TWh) in 2050. Table 2.2 shows the curtailment rate as a function of the RES penetration level without using ESS, considering three generation patterns; (i) Equal wind and solar generation, (ii) Wind vision (4:1 wind/solar), and (iii) Minimum curtailment case (calculated, i.e., 2.2:1 wind/solar).

Table 2.2: Curtailment Rate as a Function of RES Penetration Level [32]

Fraction of Annual Energy from RES (Penetration level) %	Curtailed Energy of the Available Generation from RES (%)				
	Solar	Wind	(i) Equal Mix 1:1 wind/solar	(ii) Wind Vision 4:1 wind/solar	(iii) Min. Curtailment 2.2:1 wind/solar
35	11	3.5	2.2	1.8	1.5
40	26	7	4.3	2.5	2
45	Not feasible	11	7.5	5	4
50	Not feasible	18	11	8	6.5
55	Not feasible	28	16	12.5	11

It can be seen from Table 2.2 that the amount of curtailed energy can be reduced from 16% to 11% without storage by proper management of system generation constraints. Similarly, curtailment depends upon both the energy and power capacities of the ESS.

The curtailment reduction with energy storage variation of the highest penetration level (55%) is analyzed in all three scenarios as illustrated in Table 2.3.

Table 2.3: The Role of Storage Systems in Energy Curtailment [32]

Power from ESS (GW)	Duration (Hours)	Curtailed Energy (%)		
		(i) Equal Mix	(ii) Wind Vision	(iii) Min. Curtailment
No storage	x	16	12.5	11
2	4	14.5	11.7	9.7
	8	14	11.2	9.4
	12	13.9	11	9
4	4	13	10.9	9
	8	12	10.2	8.4
	12	11.9	9.8	8
6	4	11.8	10.3	8.2
	8	10.5	9.3	7.4
	12	10	8.8	7
8	4	10.9	9.8	7.8
	8	9.4	8.8	6.7
	12	9	7.9	6.1
10	4	9.8	9.4	7.3
	8	8	8	6.1
	12	7.6	7.4	5.6

These results show that 4 to 8 hours of storage duration will reduce the curtailment in a significant way. However, further storage duration may become uneconomical with less reduction in curtailed energy. The analysis suggests that low power and short-term ESS can be used to reduce curtailment significantly with proper generation patterns of different RES [31].

2.3.3 Synchronization

To interconnect DRG systems to the utility grids, the basic and most important parameters that need to be controlled are the three-phase sequence, frequency, and amplitude of phase/line voltages. Generally, the control of multiple inverters of grid tied PV systems is designed and operated in coordination with a satisfactory operation by providing sinusoidal AC waveforms, voltage magnitudes and frequency according to the utility standards. Poor or failure of synchronization can cause instability and damage to the connected equipment, load imbalances, and even tripping of the grid itself. Numerous methods are proposed in the literature for grid synchronization of DRG such as zero crossing detection, Kalman Filter, adaptive notch filtering, phase locked loop, frequency locked loop, discrete Fourier transform, delayed signal cancellation, nonlinear least square, and artificial intelligence. Nowadays, the high penetration levels of domestic single-phase grid-connected PV systems have really raised concerns about small-scale PV integration and deserve more attention, especially in adverse grid conditions [32]–[35].

2.3.4 Frequency and Voltage Regulation

Following the discussions in Section (2.3.2), it was noted that proper frequency regulation requirements are compulsory for the penetration of higher levels of solar PV systems. The maximum penetration level also depends on the physical distribution of solar

PV arrays in a particular region. The closer PV arrays to a central station will produce more power variations due to the clouds shading, and additional frequency regulation service will be required [43], [45]. Mostly, frequency control requires activation in terms of time and needs a rapid response within a specific time interval to prevent the maximum instantaneous deviation in the system frequency. The initial time delay for frequency response activation should not be more than 2 seconds for a frequency deviation outside the operating frequency range ($\pm 1\%$) while the full activation time limit is 30 seconds. In power system operation, the frequency control is classified on the basis of different time frames as demonstrated in Table 2.4 [54], [55].

Table 2.4: Power System Control Levels Classified on the basis of Time Frames [55]

Control	Control Objective	Function	Time Frame
Inertia Response	Transient frequency dip minimization and Power balance	Transient frequency control	0–5 secs
Governor control (Primary control)	Transient frequency recovery and power balance	Transient frequency control	1–20 secs
Automatic generation control (Secondary control)	Steady-state frequency and power balance	Regulation	4 secs to 3 mins

The entire power system inertia is proportional to the initial rate of change in frequency (due to any disturbance) and dependent upon the overall inertial response of all synchronous generators in the system. However, by displacing conventional synchronous

generators with solar plants, the total system inertia will be reduced. The impact of RES integration on frequency response with different penetration levels was analyzed in [56]. In this study, two systems with a base frequency of 60 Hz were investigated, namely, the US Eastern Interconnection (EI) “a large system with an operating generation capacity of 560 GW” and the Texas Interconnection (TI) “a small system with an operating generation capacity of 76 GW”. The combined (PV and wind) rates of penetration were chosen to be 20%, 40%, and 60% [56]. As seen from the demonstrated results in Table 2.5, the maximum frequency dip in EI system was recorded after 10 seconds of a 4,455 MW generation trip while in the TI system, the maximum dip was recorded after 5 seconds of 2,760 MW generation trip respectively. Table 2.5 clearly indicates that the maximum frequency dip and the rate of frequency change are risky in case of small power systems with high shares of RES.

Table 2.5: Frequency Response of EI and TI Systems [57]

Penetration Level of RES (%)	Eastern Interconnection System			Texas Interconnection System		
	Penetration of PV (%)	Penetration of Wind (%)	System Frequency (Hz) at t=10 Sec	Penetration of PV (%)	Penetration of Wind (%)	System Frequency (Hz) at t=5 Sec
No RES	0	0	59.93	0	0	59.45
20	4.4	15.6	59.92	5.3	14.7	59.35
40	12.5	27.5	59.91	12.1	27.9	59.17
60	23.4	36.6	59.88	22.6	37.4	58.9

2.3.5 System Stability and Protection

Stability issues due to DRG integration should accurately be analyzed since it is a major concern in power system operation and control. Common reasons for stability and protection issues in power systems are sudden heavy load change (increase or decrease), tripping of generators, line switching in a grid, fault in power system equipment or transmission/distribution line, etc. Based on the time magnitude of disturbance in a power system, stability is primarily divided into steady-state stability and transient stability [57].

In [58], the impacts of different RES (small-hydro, solar PV, and wind turbine) on transient stability were analyzed by monitoring the Critical Clearing Time (CCT, in milliseconds) during a three-phase fault applied (and cleared after 200ms) at different distances from the bus to which the DRG was connected. The impacts were also evaluated for three different penetration levels (energy mode scenarios); (i) Energy import mode (when the local load demand was supplied by DRG with additional supply from the utility grid), (ii) Energy balanced mode (when power generated by DRG was enough to meet the local load demand without utility grid support), and (iii) Energy export mode (when DRG exports the excess generation to the utility grid). The fault locations (distance from the DRG bus) considered in the study were 0% (at the bus), 20%, 40%, 60%, 80%, and 100% of the total length of line between DRG and the utility grid. More oscillations and longer settling times were observed in the case when only the wind turbine was connected to the system, and the system is prone to more instability as compared to other cases when PV alone or different hybrid combinations of hydro, PV, and wind were connected to the system. Figure 2.2 (a, b, c) shows the impact of different types of RES on transient stability with different fault locations and energy mode scenarios. As seen from the mentioned figure, as the distance of fault location from DRG increases from 0% to 60% of the line, the value of CCT increases

from smaller values to maximum values and then decreases again when the fault distance increases from 80% to 100%. Moreover, it was observed that the transient stability of a dispersed DRG is better than concentrated DRG [58].

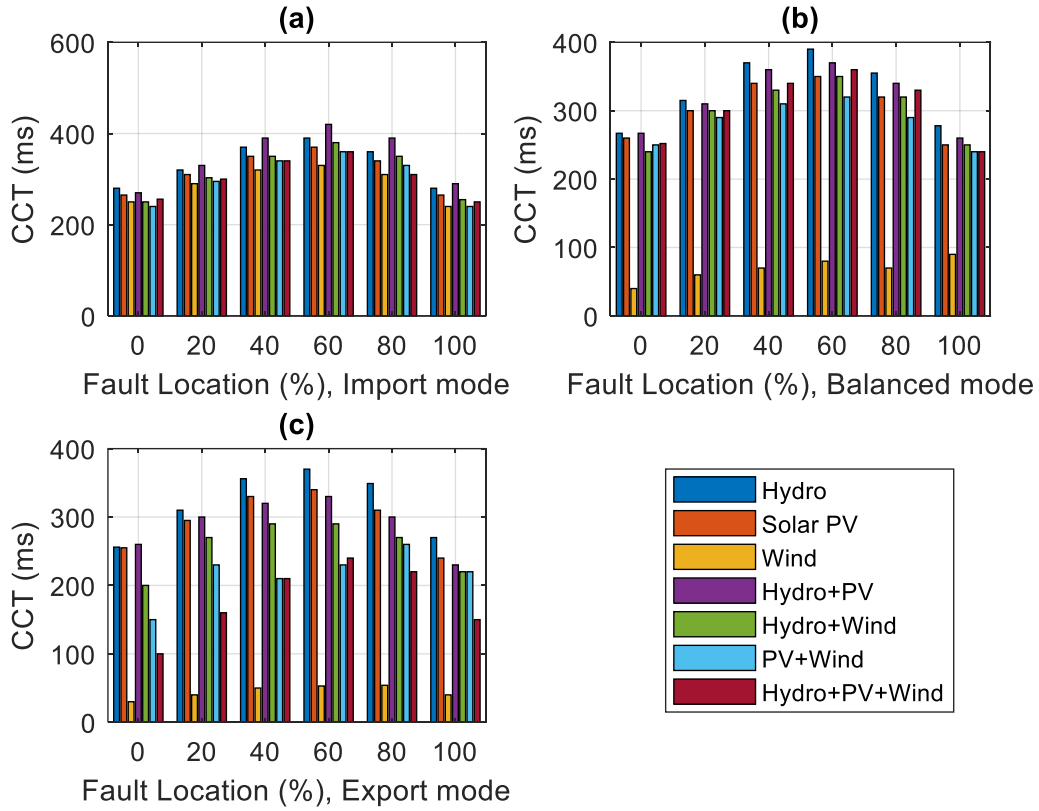


Figure 2.2: Impacts of Different RES on Transient Stability in terms of CCT [59]

The dynamic behavior of PV arrays is dependent and controlled by the interfacing inverter characteristics due to the lack of rotating mass inertia. The impacts of PV systems on utility grid stability may be positive or negative depending on their locations, ratings, and other converting factors. In case, if large PV systems replace more conventional generators, it is necessary to keep online some critical synchronous generators (even beyond their economic operating range) to maintain enough system damping. Studies concluded that location, size/power capacity, and operating mode of DRG could influence the static voltage stability of a power system [36]–[38]. Furthermore, the constant power factor mode

operation of PV inverters causes deterioration of voltage stability, whereas the voltage regulation mode operation of inverters can improve system voltage stability. Generally, large-scale PV installations are connected to the transmission systems while small-scale PV installations are distributed unequally across the distribution systems. When the output power of a small-scale PV plant sufficiently drops due to a fast-moving cloud, bus voltages in power system will also decrease. Different levels of voltage drop can occur in the phases of a typical unbalanced or asymmetrical network [59].

Further, the reactive power capabilities of large-scale and small-scale PV systems may differ from each other under both normal and outage conditions. Likewise, the interconnecting voltage level of both types of PV systems is another factor that may cause the difference. To analyze the transient stability and voltage variations in the power grid due to the interconnection of different types of PV systems, some studies were conducted at CAISO (California Independent System Operator). The studies conclude that PV systems deprived of an appropriate dynamic reactive capability contribute more to oscillations in the power system and can affect the power grid close to the PV plant. Such oscillations can cause the transient over-voltage problem as well as stability concerns such as overloading of transmission or distribution lines, generation tripping due to over-voltage, and system-wide transient instability [60].

The above paragraphs imply that the penetration level with its control results in stability issues which are still a mystery. For instance, when the power capacity of the PV plant is large enough as compared to the distribution grid capacity, short-circuit current distribution will cause a strong action of the grid protective devices. The fact is that PV power can play a significant role in changing the magnitude, duration, and fault current

direction. In such a case, the sensitivity limits of individual protection devices and cooperation of protective devices will be changed, which can directly alter the short-circuit levels of protective devices. Similarly, depending on the connection of the PV interfacing inverter with the transformer, additional ground loops may be formed, which alter the zero-sequence current or may also increase the phase voltage during the single line to ground fault and the operating characteristics of relay protection can be changed. Power fluctuations of distributed PV plants also affect the anti-islanding protection system [48], [61], [62].

2.3.6 Power Quality

Power quality (PQ) may be simply defined as a set of electrical limits or boundaries (nominal operating levels of voltage, current, and frequency) that allows a device or a part of the equipment to function in its intended style without considerable loss of performance or life expectancy. Normally, the term power quality deals with voltage fluctuations, flickers, voltage sag/swell, harmonic components in the frequency waveform, and transients [63].

The foremost impact of fast-switching PV interfacing inverters on the distribution system is an increase in the total harmonic distortion (THD) and distort the sinusoidal AC waveform. In addition, the output power variations of DRG plants may cause intolerable voltage fluctuations, voltage flickers, power swings in lines, and over/under loading conditions. A slight difference in utility grid and DRG system voltages can introduce an exponentially decaying inrush current at the time of interconnection, flowing between the distribution grid and the PV system and may cause nuisance trips and thermal stress (depending upon the percentage of PV penetration level) [64], [65].

Current harmonics with high frequencies may cause several critical issues such as resonance between the high capacitance of the interfacing inverter and the grid inductance,

overheating in transformers and capacitor banks, and false operation of protection devices in the power grid. Further, the interconnection voltage level of the PV unit also contributes to THD in the power system. Here, the PV unit connected at higher voltage levels produces less harmonic distortion and vice versa. To compensate and improve the PQ of grid connected DRG, a number of PQ improvement techniques have been developed during the past decades, classified with the help of different terminologies. These technologies include passive filters, active filters, hybrid filters, transient voltage surge suppressor (TVSS), distribution static compensator (DSTATCOM), dynamic voltage restorer (DVR), and unified power quality conditioner (UPQC). Some of them can also provide voltage regulation. However, for safe and standardized integration of large-scale RES, improvements are still required [64]–[71]. The widely developed and used techniques are listed in Table 2.6.

Table 2.6: PQ Improvement Techniques

Compensating Devices	Types	Short Details	Mitigation	Remarks
Filters [64]–[68]	Passive	Combinations of Resistors, Capacitors, and Inductors	Harmonics compensation	Economical, simple, large size, tuning, resonance
	Active	Electronic switches, capacitors, and Inductors	Voltage, current harmonics, and imbalance	Good PQ control but higher losses and high values

Table 2.6 continued

	Hybrid	Combination of passive and Active filters	Harmonics, voltage regulation, resonance suppression	Good PQ improvement at medium voltages.
UPQC [65], [68]	Based on Physical Structure	Passive and Active Filters Combinations with a self-supporting common DC bus	Voltage sag, swell, unbalance, flickers, harmonics	Different topologies have own pros and cons, light weight, high losses, high cost
	Voltage Sag Compensation Based			
Flexible AC Transmission Systems (FACTS) [67], [68], [70]	Static VAR Compensator (SVC)	Power electronic devices	Protection of sensitive loads from harmonics, transients, voltage sag, and damping oscillations	Mostly used in transmission networks
	DVR			
	DSTATCOM			
Other Devices [69], [71]	TVSS	Metal oxide varistor or a Zener diode	Suppress transient voltages	Used for sensitive loads
	Constant Voltage Transformer (CVT)	Works in resonance and core saturation	To maintain a constant voltage	Inefficient above 70% of the load

Table 2.6 continued

	Isolation Transformer	Grounded shield of non-magnetic foil between windings	To isolate sensitive loads	Effective for noise and transients
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2.4 DC Microgrids and DC Distribution

In the recent past, increased research work in DC microgrids has been observed. Recent developments in the area have shown that distributed DC microgrids fueled by RES can offer higher reliability, efficiency, cost reduction, and simplicity, by utilizing DC distribution systems. The reasons are the natural interface with RES, ESS, and electronic loads. They can be grid-connected or autonomously operated (islanded operation) [12], [15].

2.4.1 Comparison of AC and DC Microgrids

Traditional electric power systems are designed to deliver AC power from the central power station towards load centers via transmission and distribution lines. AC systems have the primary advantages of easy change in voltage magnitudes for different applications and can transmit high power over long distances. Therefore, the electrical power systems are AC-based worldwide. However, the scenario nowadays has changed and DC technologies are widely used in household, commercial, and industrial applications such as automotive, aerospace, shipboard, telecom, and in some applications of electricity transmission and distribution as well [15].

In a stand-alone mode of operation, the efficiency of DC microgrids with energy storage is better than AC microgrids on behalf of a few power conversion levels. The AC

stage losses will be eliminated in the case of a DC microgrid. In addition, DC distribution systems have shown greater efficiency in terms of reducing reactive power loss rather than standard AC distribution. It has been established that with the same resistance of power line, the DC microgrid tends to produce less copper loss while delivering the same amount of real power as the AC microgrid. Similarly, the manufacturing and installation cost of DC microgrids will also be less as the number of converters is reduced compared to AC microgrids.

The comparison between AC and DC microgrids is a complex task because each has its own benefits and detriments depending on the power levels, consumer demands, and locations. Several comparative studies [72]–[84] were carried out on AC and DC microgrids and mainly focused on the specific features and characteristics of each. Some of these studies are listed and explained in Table 2.7.

Table 2.7: Comparison of AC and DC Microgrids [72]–[84]

Characteristics	AC Microgrid	DC Microgrid	Details
Transmission efficiency	Low	High	Reactive power and skin effect losses associated with ac are eliminated in dc
RES conversion efficiency	Low	High	Transformer less, high efficiency and less number of converters are used

Table 2.7 continued

Conversion and distribution cost	High	Low	Less number of converters is used to integrate RES and ESS. Less number of distribution conductors for DC distribution.
Power quality and control	Complex	Simple	No harmonics, reactive power or phase unbalance in dc
Protection and reliability	Difficult	Simple	Difficult to guarantee seamless transition after a utility fault in ac. Dc can guarantee a smooth transient with a limited voltage variation
Protection cost	Low	High	Cost effective systems are developed for ac systems. High cost cbs and equipment under development for dc systems
Load availability	High	Low	Mostly high-power loads are designed for 3- phase ac. However, nowadays the dc loads are growing both on domestic and industrial levels

Table 2.7 continued

Frequency	50 Hz	Zero	No frequency regulation required in DC
Faults	Complex	Simple	In ac systems the faults can be unsymmetrical such as a single line to ground, multiple lines to ground, line to line, in addition, symmetrical three-phase faults. In the dc system, short-circuit either between conductors or conductor and ground.

According to the standard (LVD 72/23/EEC) [85], in DC systems, a higher voltage rating can be used than in AC systems using the same line conductors and therefore, less voltage drop can be achieved as the line inductance has no effect on DC state. It also increases the real power transfer capacity of the distribution lines due to reactive loss reduction. Furthermore, there is no skin effect, no reactive power loading, reactive power flow, frequency regulation, and power quality issues resulting in a remarkably low complexity of the system control.

Nowadays, a trend has begun where small-scale domestic and commercial consumers have started to generate power from RES and supply the excess power to the utility grid and get it back as required. For such a strategy, the bidirectional control of the power flow and conversions involves a number of power electronic devices and should be addressed properly

for efficient and quality power distribution. DC microgrid implementation is one of the possible solutions, which can minimize power conversion loss significantly. Indeed, AC power is converted into LVDC using a high-efficiency rectifier when entering the DC microgrid system and then distributed directly to DC loads connected to the DC microgrid. Furthermore, DRG and rooftop PV systems can feed DC loads directly, eliminating the double conversion loss (DC/AC and then AC/DC) through the DC distribution, which would be required in the case of AC distribution and DC loads. Normally, the DC microgrid is connected to the prevalent three-phase AC utility grid via a bidirectional DC/AC converter, with such connection, the conversion loss can be reduced from 32% to 10% [74], [81], [82].

Moreover, the additional positive impact of the distributed DC microgrids is high reliability during disturbances in the power grid and can provide a reliable power supply to its own connected load during islanded mode of operation often referred to as a seamless switch. In AC microgrids, it becomes more difficult to switch the energy storage converters accordingly and distinguish between the potential low voltage ride through (LVRT) and seamless switch. The reason is the decrease in distribution voltage that can be observed over a vast area due to the voltage dip caused by the transmission system. As stated in the grid codes, RES should remain connected for a short duration of low voltage caused by the connection of heavy loads or grid faults such as short-circuits or lightning strikes. The instantaneous and simultaneous trips of AC microgrid can cause further transient events after the utility grid fault. The utility connected AC microgrid operators may require a pre-defined seam for not enough low voltage drops. Hence, for the storage systems that are connected directly to the utility grid, the voltage cannot be restored by switching immediately into the voltage regulation mode after the detection of a voltage dip. Further, the voltage detection approaches may cause further delay in the voltage detection process, making another

undesirable attribute for a seamless transition during the islanded operation. On the contrary, after detecting an abnormal DC voltage variation in DC microgrids, DC side energy storage system can immediately switch into the voltage regulation mode and facilitate the DC voltage in reacting time of milliseconds regardless of the common DC/AC converter operating mode and the utility fault occurrence, and thus providing better power quality [83].

From a control point of view, DC power system stability is ensured only by constant DC voltage amplitude, while for an AC system, voltage amplitude, as well as the frequency or angle must be regulated simultaneously. Furthermore, the phase unbalance issue due to the vast implementation of single-phase loads and DRG in the three-phase AC utility grids needs refined techniques to cope with the unbalanced components. On the basis of the given difficulties, one can say that DC systems provide better controllability than AC systems. Since AC-based systems are dominating worldwide, an extensive range of electrical equipment and loads are designed for standard AC supply. However, converter-fed loads such as TV sets, computers, LEDs, routers, and other electronic appliances are logically more compatible with a DC supply. By using a common DC bus system, the cost of the rectifying side can be greatly reduced with better efficiency. AC systems have currently an advantage over DC systems in the area of the protection system. The first and foremost reason is the vast protection theory applied to AC systems. Secondly, the AC system is established with developed techniques associated with protective equipment. Finally, AC circuit breakers can easily distinguish the arcs due to the zero-crossing nature of AC current. However, DC systems have no zero-crossing naturally, thus sophisticated techniques and high-cost DC circuit breakers are the major disadvantages in DC systems [84], [85].

2.4.2 AC Microgrids Pilot Projects

Nowadays, microgrid (from kilowatts to gigawatts) deployments can be seen around the world in metropolitan cities including residential, industrial, and commercial buildings in urban as well as rural/remote areas using both conventional and renewable sources to meet the wide-ranging needs of different communities. The size and number of the energy sources or the types of technologies that can be used are not limited, however, the smart microgrid concept has been usually adopted for utilizing DRES.

Navigant Research has identified 2,258 installed and planned microgrid projects globally, representing nearly 20GW of power capacity [86]. Some well-known AC microgrid projects deployed in different countries are demonstrated in Table 2.8 [86], [87].

Table 2.8: AC Microgrid Projects around the World [86], [87]

Project/ Location	Power Sources	Storage	Structure	Control	Load
Utility Microgrid at Los Alamos, New Mexico.	PV	Battery	Radial	Decentralized	Residential
Microgrid at Albuquerque, New Mexico.	PV, Fuel Cell, Gas, Combined Heat & Power (CHP)	Capacitor	Radial	Decentralized	Residential, Commercial, Motor
Laboratory scale microgrid, New Jersey.	PV	Battery	Radial	Centralized	Residential, Motor

Table 2.8 continued

Palmade Microgrid, California.	Wind, Hydro Diesel, Gas	Capacitor	Radial	Decentralized	Residential, Commercial, Static
Mad River Park Microgrid, Vermont.	PV Diesel,	Battery	Mesh	Decentralized	Residential, Commercial, Industrial
CERTS Testbed, Ohio.	Gas	Battery	Mesh	Decentralized	Residential
RIT Microgrid, New York.	PV, Wind, Fuel Cell	No	Mesh	Decentralized	Residential, Static, Motor
NTUA Microgrid, Athens.	PV, Wind	Battery	Radial	Agent based	Static
Genoa University, Genoa.	PV, Wind, CHP, Gas	Battery	Mesh	Decentralized	Residential
HFUT Microgrid, China.	PV, Wind, Fuel Cell, Hydro, Gas	Battery	Mesh	Agent based	Static, Motor
NUAA Testbed, China.	PV, Wind,	Battery	Radial	Centralized	Static, Motor
Tianjin University Testbed, China.	PV, Wind, Diesel	Battery	Radial	Centralized	Static
Test Microgrid at IET, India.	Fuel Cell	No	Radial	Centralized	Static
Boston Bar, British Columbia, Canada.	Hydro, Diesel	No	Radial	Decentralized	Residential
Ramea wind-diesel Microgrid, Canada.	Wind, Diesel	Battery	Radial	Decentralized	Residential
Fortis-Alberta Microgrid, Alberta.	Wind, Hydro	No	Radial	Centralized	Industrial
Bronsbergen Park Microgrid, Zutphen, Netherlands.	PV	Battery	Mesh	Centralized	Residential

Table 2.8 continued

Am Steinweg Microgrid, Stutensee, Germany.	PV, CHP	Battery	Mesh	Agent based	Residential
Nimbus Microgrid Testbed, Cork, Ireland.	Wind, Fuel Cell, CHP	Battery	Radial	Centralized	Residential
INER Microgrid Testbed, Taiwan.	PV, Wind, Diesel, Gas	Battery	Mesh	Decentralized	Static, Motor
MSEDCL at Wani Area Microgrid, India.	PV, Biomass, Diesel	No	Mesh	Decentralized	Residential, Commercial
Aichi Microgrid, Tokoname, Japan.	Gas	No	Radial	Centralized	Commercial, Industrial
Kyoto eco-energy Microgrid, Kythnos Island, Japan.	Gas, Diesel	Battery	Mesh	Centralized	Residential
Hachinohe Microgrid, Hachinohe, Japan.	Gas	Battery	Radial	Centralized	Commercial, Industrial
Microgrid test facility in Yokohama, Japan.	PV, Wind, Gas	Battery	Remote	Centralized	Commercial, Industrial

2.4.3 DC Microgrids Pilot Projects

In fact, the majority of microgrids comprise of traditionally dominated three-phase AC architecture [75], however, to reduce the power losses, DC microgrids and DC distribution systems are being deployed for applications where the DRES, ESS and end-user loads are natively DC. Some well-known DC microgrid projects are demonstrated in Table 2.9 [87], [88].

Table 2.9: DC Microgrid Projects around the World [87], [88]

Project/ Location	Power Sources	Storage	Structure	Control	Load
University of Miami Testbed, Florida.	PV, Fuel Cell,	Battery	Radial	Decentralized	Residential
Sandia National Lab Testbed, Washington DC.	PV, Wind, Diesel	Battery	Radial	Decentralized	Residential , Static
University of Texas, Arlington, Texas.	PV, Wind, Fuel Cell, Diesel, Gas	Battery	Radial	Decentralized	Residential , Static
Florida International University, Miami, Florida.	PV, Wind, Fuel Cell,	Flywheel	Radial	Centralized, Agent based	Residential , Motor
Hawai Hydrogen Power Park, Hawaii.	PV, Wind, Fuel Cell	Battery	Radial	Centralized	Residential , Static
CESI RICERCA DER Testbed, Moneta, Virginia.	Solar Thermal, PV, Wind, CHP, Diesel	Flywheel	Radial	Centralized	Residential
University of Nottingham	Wind	Battery	Radial	Decentralized	Residential

Table 2.9 continued

University of Technology, Compiègne (UTC) Testbed, France.	PV, Fuel Cell	Battery	Radial	Decentralized	Motor
University of Seville Testbed, Spain.	PV, Fuel Cell	Battery	Mesh	Decentralized	Residential , Motor
Queensland University of Technology, Australia.	PV, Wind	Battery	Radial	Decentralized	Residential , Motor

2.5 Design Standards for DC Microgrids

Although DC systems have been studied intensively in recent years, however, the DC microgrid design still lacks common standards and regulations to guarantee its interoperability and widespread acceptance in industrial and commercial applications. The important design consideration of DC networks is the voltage levels, which are highly dependent on the scale/size of the microgrid. Research studies indicate that 380V DC is the most efficient and cost-effective solution with the least conversions at the present level, especially for data/telecom centers and commercial applications, while 24V or 48V DC auxiliary voltages can be selected for low power rating appliances. Typically, voltage levels can be varied according to the size of the DC microgrid and load requirements. For example, Virginia Polytechnic University proposed a DC nano-grid where two voltage levels (380V and 48V) coexist to fulfil the requirements of different appliances. Similarly, in Finland, a 1500V DC microgrid is built up whereas a proposed DC microgrid in Japan currently uses

± 170 V DC. Table 2.10 demonstrates some practical examples of DC microgrids with different voltage levels [68], [70], [74].

Table 2.10: Some Existing Examples of DC Microgrid Voltage Levels

Country	DC Microgrid	Voltage Levels	Capacity	Applications
Sweden	UPN AB	24–350/380LVDC	≥ 5 MW	Data Centre IBM
United States	US Intel Corp.	400 LVDC	≥ 5 MW	Data Centre
Japan	NTT Group	380/400 LVDC	≥ 5 MW	Data Centre
New Zealand	Telecom NZ	220 LVDC	0.5–5MW	Data Centre

Several practical standards have been developed by different global organizations to promote DC microgrids and DC distribution systems. The latest standard IEEE SA-P2030.10 (with the title ‘Standard for DC Microgrids for Rural and Remote Electricity Access Applications’) to provide power for remote and rural applications [89]. Chinese Communication Standard Association (CCSA) has also set standards for the use of DC power distribution in data/telecom centers. These standards (including YD/T2378-2011, YD/T 2089-2016, YD/T 3091-2016, YD/T 2556-2016) define the technical requirements, terminology definitions, inspection rules, evaluation requirements, testing, and marking methods for 240/336 V DC distribution systems in data/telecom centers [90], [91].

Recently, different DC distribution standards have been updated and published such as the international telecommunication union (ITU) standards (ITU L.1201 (2014), ITU L.1202 (2015) and ITU L.1203 (2016)) [92], [93], IEEE DC @ Home [94], the Rebus standard [95], European standard (ETSI EN 300 132-3-1) [96], the National Electrical Code (NEC) [97], IEEE Standard 1547 [98], the International Electrotechnical Commission (IEC) standards IEC SG4 [99], etc. Further, EMerge Alliance is an industry association that standardizes and promotes DC microgrids with advanced architectures and control systems in occupied spaces, telecom/data/ centers, and building services with a 380V DC voltage level to energize lightning, air conditioners, racks, servers, and wireless internet devices [100].

Apart from the aforesaid standards, special purpose standards can also be found in literature such as military standard, MIL-STD-1399 (used as a standard for DC equipment in shipboard power systems) [102]. Some of the proposed standards for DC microgrids are reviewed in Table 2.11.

Table 2.11: Practical Standards Developed for DC Microgrids

Standard	General Description	Scope	Year
IEEE SA-P2030.10 (PAR for a New IEEE Standard)	DC Microgrid standard for Rural and Remote Applications	RES to be used to provide power for remote and rural applications. Standardized products and services	2016
ITU L.1201, 1202, 1203 (International Telecommunication Union)	DC power distribution (up to 400V) in Data/Telecom centers	Structure, efficiency, environmental impacts, marking and color coding for DC distribution in telecom/data centers	2016 / 2017

Table 2.11 continued

YD/T (Chinese Communication Standard Association)	DC distribution (240/336V) in data/telecom centers	Technical requirements, definitions, rules, test and marking methods for 240/336 V DC distribution	2016
IEEE DC @ Home	Homes powered by DC supply	LVDC microgrids in Houses with losses evaluation	2013
Rebus TM	A standard for DC clean power distribution	Hybrid operation of renewable generation with existing AC system. Use of 380 V DC common bus with permissible voltage variation, loads and energy storage systems	2013
ETSI EN 300 132-3-1	Input power interface to data/telecom equipment. DC sources up to 400 V	Designed for data/telecom equipment.	2011
NEC	Legal codes for electrification and safety	Introduction of DC technology in articles 393, 625, 690 and 692.	2011
IEEE 1547	Interconnecting requirements for distributed RES with electric power systems	Designing standards for DC systems. Requirements of normal and abnormal operation for distributed sources	2009

Table 2.11 continued

IEC SG4	1500V and below DC distribution systems	Standardization of telecom/data centers, commercial buildings, etc. Energy efficiency, protection, EMC, grounding, and life cycle of equipment. 100% DC architecture or Hybrid AC-DC	2009
EMerge Alliance DC microgrid (MG)	Standards for data centers and occupied spaces or buildings	Recommended control system and architecture for DC microgrids.	2008
MIL-STD-1399	Electrical interfaces for shipboard equipment	Requirements of DC equipment used in shipboard power systems.	1992

2.6 DC Microgrid Architectures

Driven by the specific application of DC microgrid, several hardware topologies have been proposed, tailored for simplicity, flexibility, control approach, and reliability. Some of the practically implemented topologies are reviewed and discussed in the following subsections.

2.6.1 Single Bus Topology

The most common and frequently deployed topology in residential, commercial, and industrial applications is single bus topology. In its simplest configuration, the storage system can be directly connected to the DC bus as shown in Figure 2.3, however, directly

connected storage raises the issues of uncontrollable bus voltage and circulating currents, resulting in the reduced lifespan of the battery [12], [103], [104].

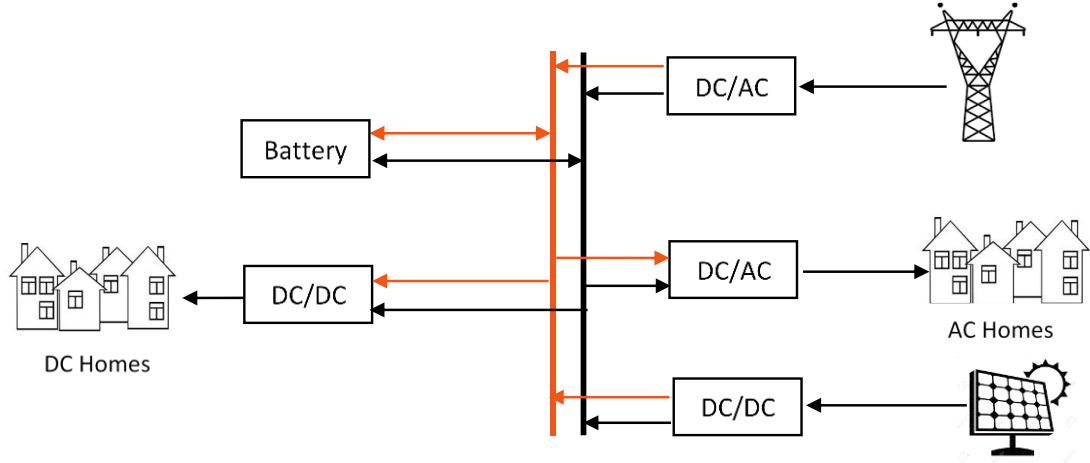


Figure 2.3: Single Bus DC Microgrid with Directly Coupled ESS [12]

For more flexible control and enhance the system reliability, a dedicated interfacing converter can be used between LVDC bus and storage system as shown in Figure 2.4.

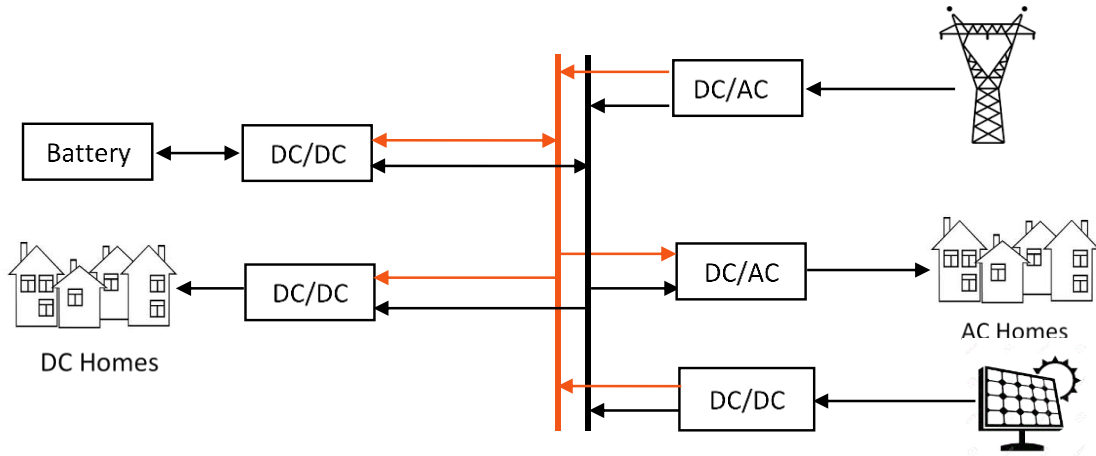


Figure 2.4: Single Bus DC Microgrid with Converter Interfaced ESS [12]

To overcome some technical issues, an alternative remedy with a bipolar regulated single bus structure operating on ± 170 V has been proposed in [105] as depicted in Figure 2.5. The main advantages of the modified topology are the availability of three voltage levels

(340 V, +170 V, and -170 V) for load side DC-DC converters, and increased reliability with the double supply lines [105].

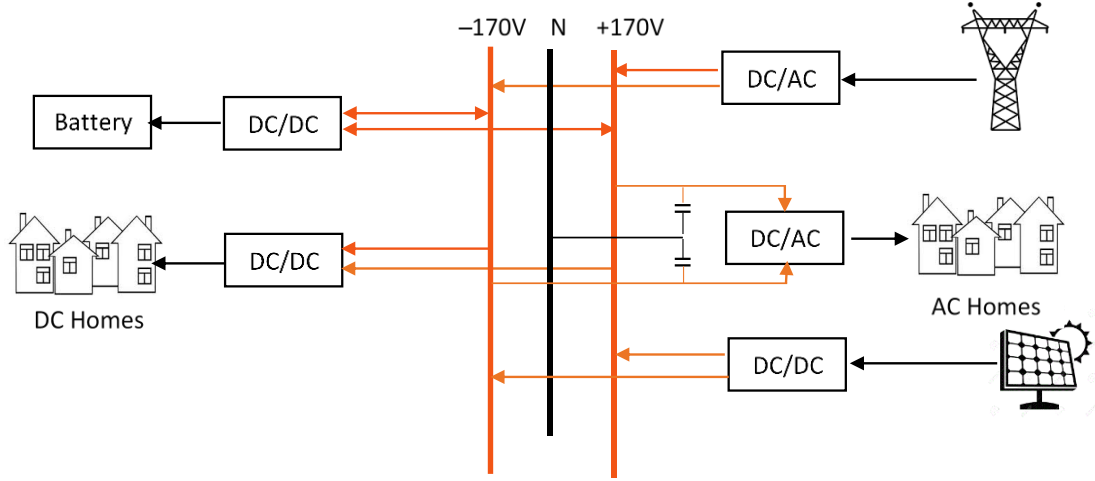


Figure 2.5: Bipolar Single Bus DC Microgrid [12]

2.6.2 Multi Bus Topology

To achieve higher availability and reliability, DC microgrids may be extended to multi bus topology configurations with simultaneous supply from multiple buses to enhance system efficiency. A modified topology based on the principle of automated hot swap between buses using auctioneering diodes method is shown in Figure 2.6 [12].

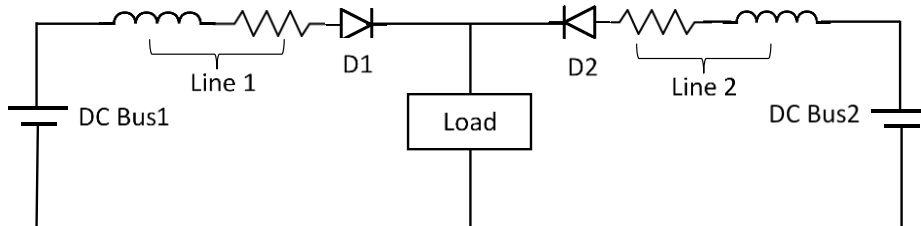


Figure 2.6: Dual Bus, Separately Fed DC Microgrid [12]

Besides the multiple bus configurations, an alternative solution is the use of multiple DC microgrids cluster configuration (as seen in Figure 2.7) which enables each DC

microgrid to inject or absorb power from neighboring microgrids in case of surplus or shortage of power, respectively [106].

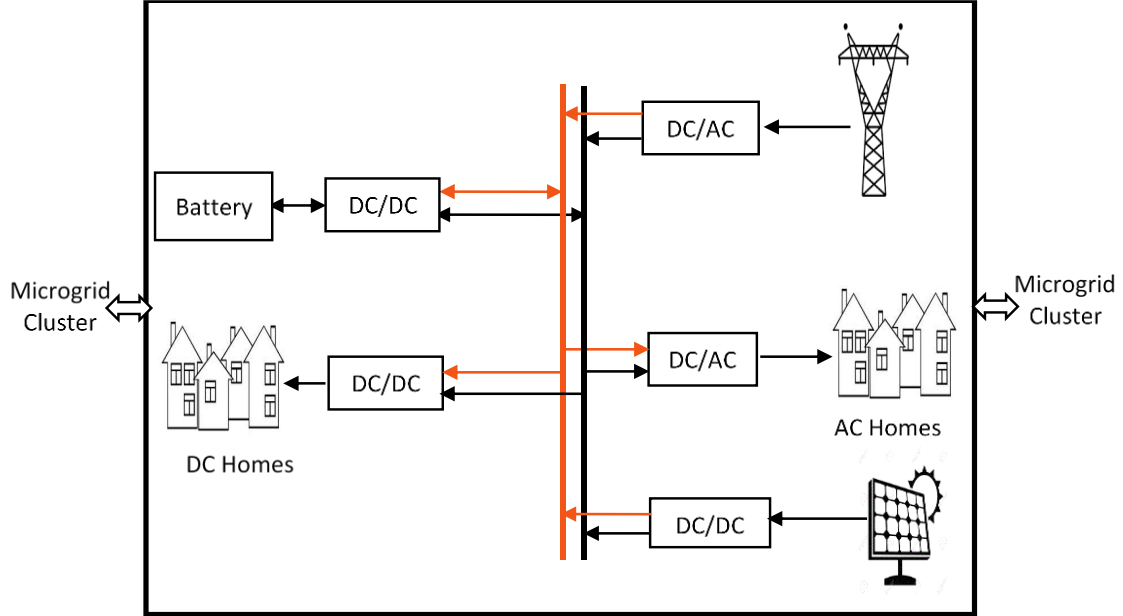


Figure 2.7: DC Microgrids Cluster [106]

Another configuration is presented in [107] for LVDC distribution systems when connected to a medium voltage AC system through a solid-state transformer (SST) as shown in Figure 2.8.

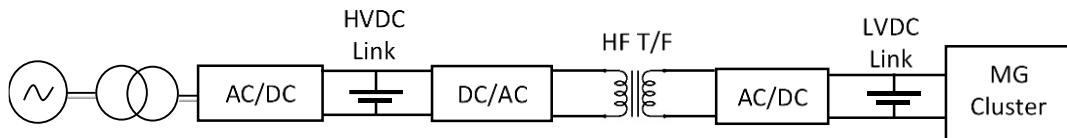


Figure 2.8: SST Interfaced DC Microgrid [107]

It is noted that SSTs are still in the development stage and are deemed to be true enablers of future DC distribution architecture. Many academic and industrial projects such

as UNIFLEX, FREEDM, and HEART are working to push this technology into future distribution systems [107].

2.6.3 Ring Bus Topology

Ring bus topology was proposed to maximize the reliability and flexibility of DC microgrids during fault conditions and periodic maintenance with a bidirectional supply as shown in Figure 2.9. The smart switches controlled by intelligent electronic devices (IEDs) are connected to each node as well as between nodes. The IEDs will disconnect the faulty branch automatically [108].

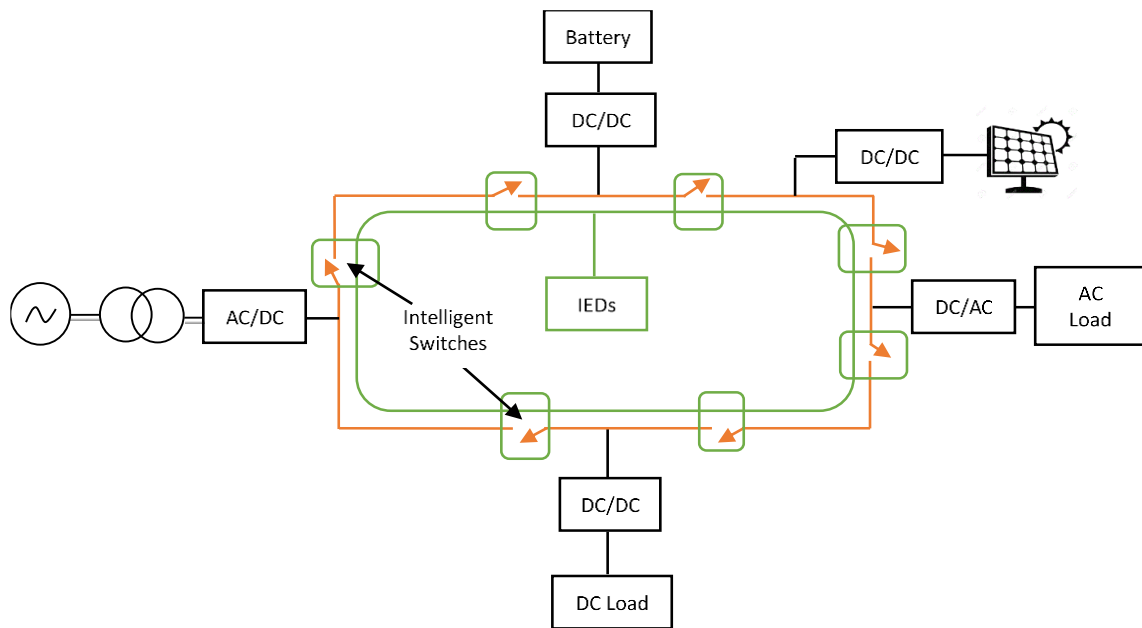


Figure 2.9: DC Ring Bus Topology [12], [108]

2.7 DC Microgrid Control Strategies

In order to guarantee an efficient coordinated operation of different units in a DC microgrid, effective control strategies for interfaced power converters should be implemented to achieve flexible voltage control and precise power sharing among parallel connected converters. Further, the constant power behavior of power converters adds

nonlinear effect that makes system control unstable. The main control objectives include efficient voltage regulation and power sharing control among different DRES, optimization and maximum utilization of DRES, and stable operation in all operating conditions [19].

From a control point of view, there is no unique control strategy for a specific microgrid. Rather it depends on the architecture, its configuration, and the components used in a microgrid [113]. DC microgrid control strategies can be classified into Basic control strategies and Hierarchical control framework (two or three levels of control). The overall classification chart can be seen in Figure 2.10.

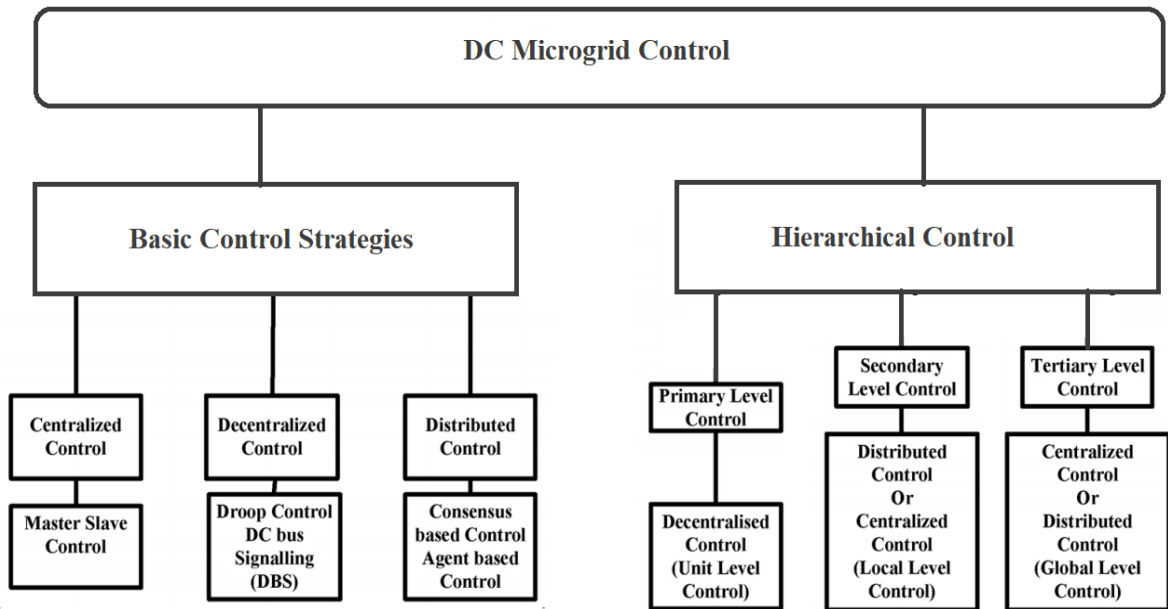


Figure 2.10: DC Microgrids Control Strategies

Characterized by communication level between microgrid components, basic control is achieved by three methods including centralized control, decentralized control, and distributed control. In hierarchical or multilevel control, a basic control strategy is implemented at each level of control.

2.7.1 Centralized Control

Centralized control is simple and usually implemented in source-based small DC microgrids. All units are linked in a centralized environment using dedicated two-way communication links. The centralized controller collects information on all state variables from component-level sensors and it is responsible for processing and decision-making to control all the microgrid components (see Figure 2.11). This control strategy provides strong observability and control of the whole system, however, a single-point failure of communication results in reduced reliability and flexibility [114].

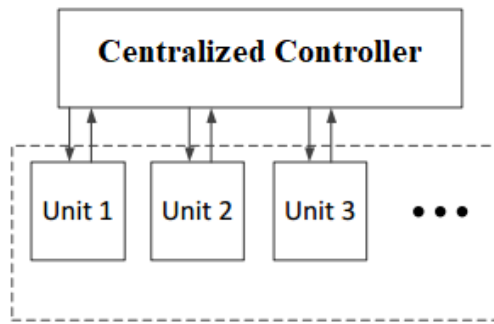


Figure 2.11: Centralized Control Strategy

The master-slave control scheme is a common example of centralized control. Different researchers have implemented master-slave control with different techniques [115]–[117] to overcome some of its limitations.

As shown in Figure 2.12, in this control, one of the converters (called Master converter) operates as a Voltage Source Converter (VSC) to regulate the DC bus voltage while all other converters (called Slave converters) follow the master converter and work as Current Source Inverters (CSI). The main weaknesses of centralized control are high dependency on a single master controller, poor scalability, and the requirement for supervisory control [19].

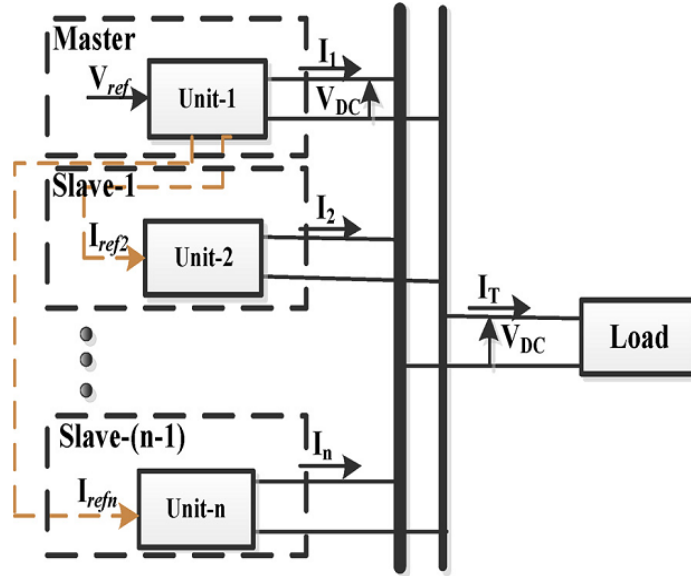


Figure 2.12: Master-Slave Control [19]

2.7.2 Decentralized Control

Decentralized control does not depend on communication links and independent controllers are used to control individual units using local state variables data as shown in Figure 2.13.

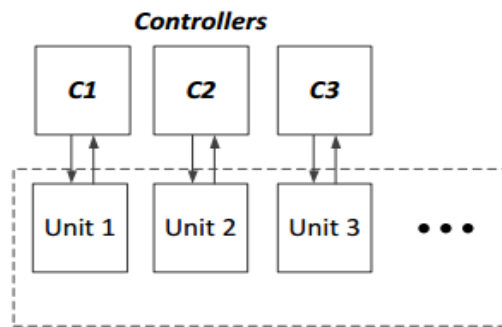


Figure 2.13: Decentralized Control Strategy

In this sense, decentralized control is considered more reliable, however, some performance limitations arise as no information is shared with other units in the system and all units operate autonomously.

The widely implemented decentralized control strategy for parallel connected converters is droop control, usually adopted for power sharing between multiple converters. In a droop control strategy, the output current and power are selected as the droop feedback. The droop principle for the current droop is depicted in Figure 2.14(a) and the power droop is shown in Figure 2.14 (b).

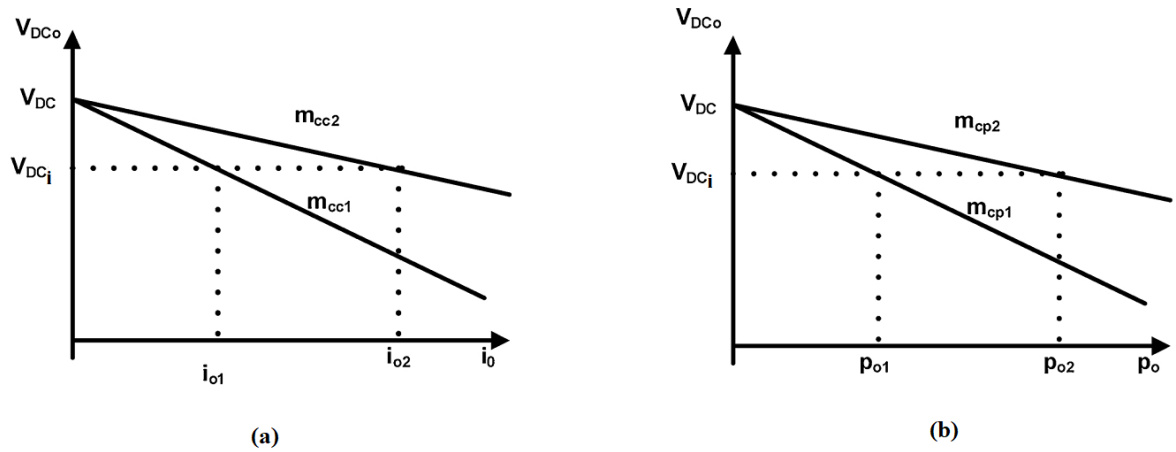


Figure 2.14: Droop Curves (a) Current Droop (b) Power Droop

The characteristic Equations can be written as:

$$V_{DCi} = V_{DC} - m_p i_{oi} \quad \text{Equation 2.1}$$

$$V_{DCi} = V_{DC} - m_c P_{oi} \quad \text{Equation 2.2}$$

The terms V_{DCi} represent the reference value of output voltage of the i_{th} converter, V_{DC} is the DC bus voltage, m_c and m_p are the current and power droop coefficients of the converter. Here i_{oi} and P_{oi} are the output current and power of i_{th} converter. The above equations show that the values of droop coefficients reduce the DC bus voltage with an increase in load current and degrade the current sharing as well. The higher values of the droop coefficients result in higher current sharing accuracy but a more damped system and increased voltage deviation. To minimize error and trade-off between current sharing

accuracy and voltage deviation, the droop coefficients should be selected to achieve optimal coordinated operation [118].

Generally, the decentralized control is considered more flexible and reliable, however, insufficient information about other units, load dependency in islanded mode, incompatibility with non-linear loads, circulating currents in DGs, and poor transient performance degrade the overall performance of the system. Different researchers have employed improved droop control strategies for the parallel operation of power converters in literature to minimize the DC bus voltage drop due to the virtual droop resistance with an increase in output current. Also, the unequal line resistances degrade the current-sharing accuracy as well as DC bus voltage regulation [87], [118].

2.7.3 Distributed Control

Recent advancements in communication technologies bring the concept of distributed control, where the advantages of both centralized and decentralized control strategies are combined and implemented in a distributed fashion as shown in Figure 2.15.

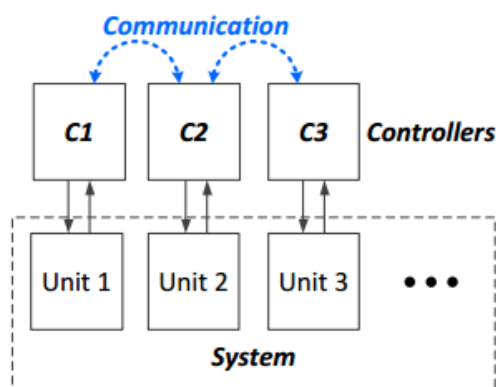


Figure 2.15: Distributed Control

In this method, the local controllers communicate and share essential information with neighboring units in order to provide coordinated control of all the units to achieve

higher power sharing accuracy and improved voltage regulation. This approach eliminates the single point failure of the whole system: because the system can function even if a communication failure occurs between some units. To specify the exchange of information between different DG units, a consensus algorithm (interaction protocol) is defined for all DG units to solve distributed optimization problems and achieve flexible control. The main drawbacks of distributed control scheme are bus voltage deviation and poor performance during system disturbances due to communication delay and complexity of analytical performance [84], [120].

2.7.4 Hierarchical Control

The hierarchical control (Figure 2.16) is a three-levels control architecture. At the primary level, stabilization of voltage magnitude and power sharing among sources are ensured. At the second level, steady-state voltage deviations induced by the primary control are compensated. Power management and optimization are dealt with at the tertiary level.

Output voltage stability and load current sharing control among power sources during load or source power variations is the key objective in DC microgrids. Output voltage fluctuations of power converters and mismatches between line resistances of different sources can degrade the active current sharing and can also affect the voltage stability of DC microgrids. Generally, a decentralized model-based droop control technique (combination of primary and secondary control) for load current sharing is used for islanded DC microgrids [84], [110], [113], [121]–[124].

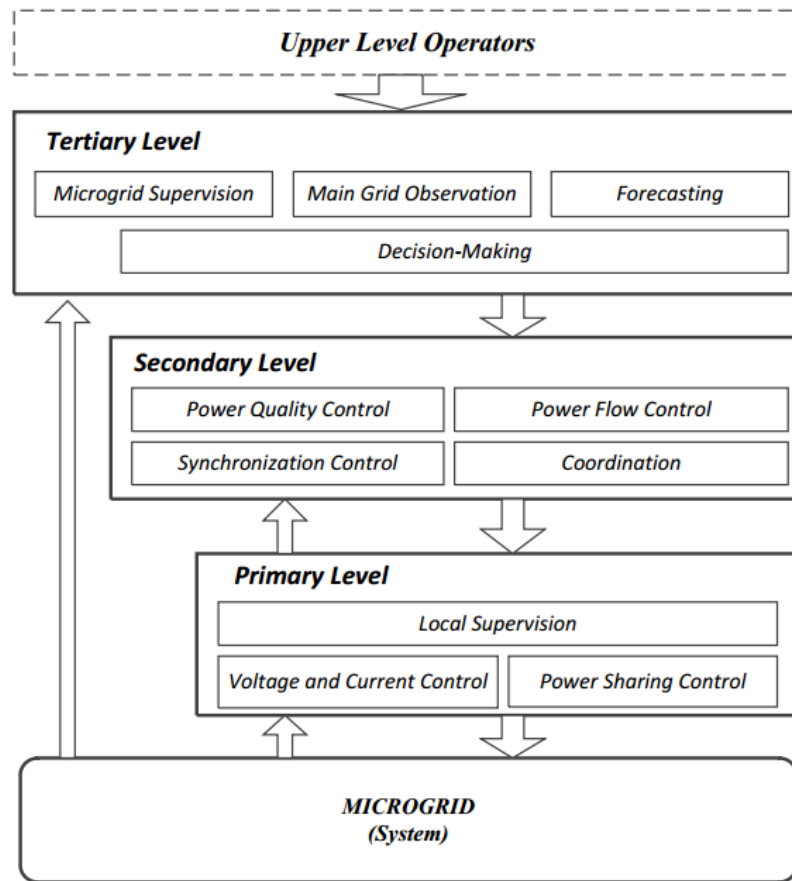


Figure 2.16: Hierarchical Control

2.8 Impact of Faults on DC Microgrid Control

The development of an effective protection strategy is mainly dependent on the dynamic behavior of DC microgrid under various fault conditions. Generally, the short-circuit fault is the decisive fault condition that generates maximum fault currents and is the basis of the protective equipment selection [123]. The current changing rate (di/dt) during short-circuit fault conditions in a DC system is much higher than AC system for the same voltage and power levels. This is due to the absence of natural zero crossing in DC circuits and the lower inertia of power electronics converters, making the fast fault current interruption more difficult in DC microgrid systems [122], [124]. To overcome the slow operation of traditional circuit breakers, robust and efficient semiconductor-based circuit breakers for fast DC fault interruption have got attention as an optimal solution. Such DC

circuit breaker senses the abrupt change in IGBTs current and terminal voltage to detect an abnormal condition and avoid malfunctioning [128]. The isolated LVDC distribution networks consisting of RES and loads are more prone to failure due to the small impedance value of the DC lines. As a result, the small transient disturbances pose great challenges for fault detection, resulting in the discoordination of protective devices. In this view, DC fault current limiters (FCL) are proposed in the literature to decrease the abruptly rising fault current and gain time for fault detection and protection devices [126], [129].

2.8.1 Fault Current Limitation Techniques in DC Systems

Remarkable progress in high-voltage DC (HVDC) transmission systems has laid solid foundations for LVDC distribution systems, however, the absence of mature and reliable fault detection and protection technologies constrains the widespread applications of LVDC distribution systems [130]. However, LVDC distribution lines/cables are relatively short compared to HVDC systems, therefore, the protection methods of HVDC systems such as traveling-wave protection are not suitable for LVDC distribution systems. Due to the transient and destructive nature of DC short-circuit faults, besides the robust methods of fault detection and isolation, current limiting technologies must be considered comprehensively for reliable future DC grids [131]–[133].

Fault current limiters (FCLs) have been applied in power generation, transmission, and distribution networks to prevent damage from faults, protection improvement, stability enhancement, fault ride through capability enhancement, and to avoid the inevitable upgradation of different equipment. An ideal current limiter should have zero impedance during normal operations, be able to get instantly involved to limit the fault current with high impedance during fault conditions and provide a fast recovery after the fault. Different types

of fault current limiters such as resistive, inductive, resonance, DC reactor, superconducting, non-superconducting, and flux-lock have been proposed in literature. Classical and commonly used FCLs in AC systems include series current limiting reactors, air-core reactors, and high impedance transformers. However, they reduce the voltage stability of the system owing to constant impedance and power losses during normal operations [128]. Other advanced and most commonly used FCLs are solid-state FCLs, series and/or parallel resonance-type FCLs, superconducting FCLs, and saturated core FCLs [129], [130]. The FCL used in power systems are broadly classified as: superconducting and non-superconducting [126], [127]. A simple classification tree of superconducting FCL (SFCL) and non-superconducting FCL is shown in Figure 2.17, however, their detailed features and operating principles are not briefly explained as it is out of the scope of this study.

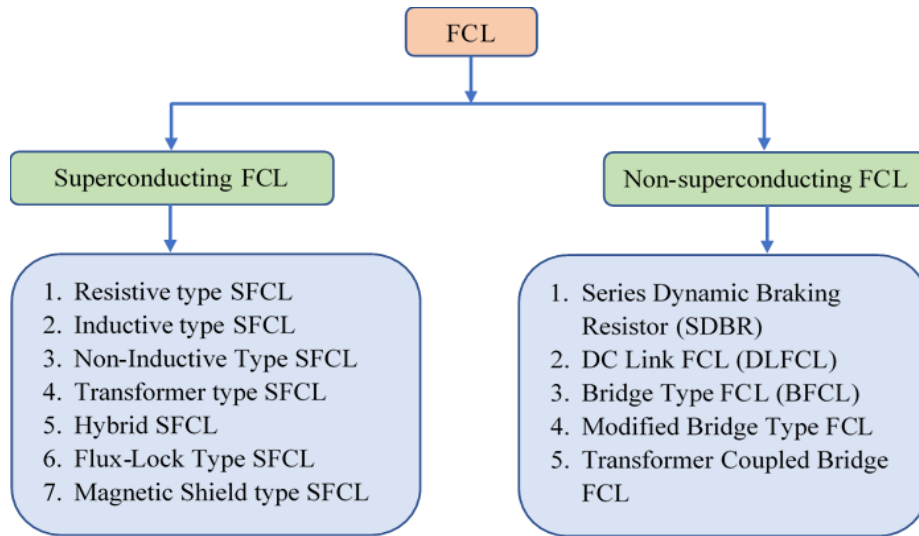


Figure 2.17: FCL Classification

2.9 Related Studies and Research Gap

The advanced, robust, and reliable communication technologies have promoted the hierarchical/multilevel control mechanism as one of the best choices for microgrid control. Although a variety of basic control techniques (with and without communication) are

adopted at each level of the hierarchical control structure, the primary ensures the load sharing among the power converters while the voltage regulation is obtained at the secondary control. The tertiary level control establishes the energy management system and communication with the Distribution System Operator (DSO) [119]. In a stand-alone DC microgrid, only primary and secondary levels of hierarchical control are implemented in different fashions to achieve power sharing and voltage regulation. To implement a distributed control strategy for DC microgrid control, a consensus algorithm is adopted at secondary control level based on information interchange using advance communication technologies.

A master-slave robust control strategy for a single DC microgrid is presented in [115] where the storage unit converter serves as the master while the converters of PV and fuel cell (FC) sources act as the slaves. The master controller is a cascaded voltage controller composed of a proportional integral controller and a sliding mode controller. The slave controllers are responsible for load power control while the master controller stabilizes the microgrid voltage and mitigates voltage fluctuations due to load variations. The performance of the proposed methodology is verified using MATLAB/Simulink. The study has not considered the line impedances or overload conditions.

The study presented in [116] has proposed an adaptive optimal control approach with parameters estimation under master-slave operation for DC microgrids to eliminate voltage deviations. The proposed approach utilizes the current control and recursive least squares methods and can be implemented on both primary and secondary control levels. Also, a linear-quadratic regulator (LQR) is adopted to improve the stability of the microgrid in a master-slave configuration with less information interchange. This feature increases variable

integration of DRES and interoperability. However, an error in parameter estimation can degrade its performance. Also, the performance of the proposed approach is not tested under different load conditions and system disturbances.

A distributed optimal control strategy for DC microgrids is presented in [138]. This strategy allows each DC microgrid to adopt one of the three control strategies (power control, voltage control and droop control). The secondary controller can provide commands for all these strategies. The strategy is based on optimal power flow and second order cone program using a dynamic solving algorithm. This algorithm provides control commands for power control, voltage control and current sharing control. The main advantage of the proposed control is that each microgrid doesn't change its original control strategy, however, the complex and excessive information exchange is the key limitation of the proposed technique.

A communication less droop-based sliding mode controller with an improved nonlinear droop model is developed in [139] to minimize the trade-off between voltage regulation and power sharing in an isolated DC microgrid. The proposed controller uses a fuzzy approximator to determine the control parameters. The fuzzy approximator updates the control parameters by applying a small intelligent change to compensate for various load deviations resulting in reduced control action stress. Based on the results presented, it is claimed that the proposed control is fast and accurate under various operating conditions, however, the performance of control during system disturbances is not analyzed.

To enhance the operation of DC microgrid during steady-state conditions and after small disturbances in the microgrid system, a controller reconfiguration algorithm is proposed in [140]. The proposed control algorithm follows the set-points determined by a higher-level controller during normal operating conditions but after any disturbance in the

microgrid, the mismatch ratio is shared using a separate loop to enable accurate current sharing after the disturbance is cleared. The recovery of power sharing is presented under small disturbances where the power converters are not pushed to supply power beyond their maximum ratings.

An adaptive droop-based FCL for a standalone LVDC microgrid to facilitate the protection system is proposed in [141]. The fault is identified when the voltage and current of individual converter exceed the threshold values. The fault current limitation is achieved by varying the values of droop resistances using an additional droop within the main control and sending a signal to the protection system. This extended-droop FCL scheme limits the fault current using an adaptive virtual droop resistance to maintain the output voltage of converter by reducing the current flow from converter. This reduction in the current flow helps the protection system by increasing the fault clearing time. Moreover, to isolate the faulted converter or distribution line, a trip signal is sent to the corresponding DC bus circuit breakers. The main limitation of this scheme is that any communication delay or data loss can lead to a malfunction of the protection system.

The precise ratio-based current sharing without significant degradation of the system voltage profile during various operating conditions and system disturbances is the key desired feature of the droop-controlled DC microgrids. The performance of the control system might be affected by any disturbance or fault in the system especially when different DG units are connected to the DC bus with unequal line impedances. This is because the line impedance has great role in limiting the magnitude of fault currents.

On the other hand, the commercially available protection devices for DC systems nowadays (such as fuses and circuit breakers) inherently introduce large time constants and

time delays before activation. In the case of fast-rising DC fault current, the fault current interruption is accompanied by an arc (more hazardous from a safety point of view). Such arcs are naturally extinguished in AC systems due to half-cycle tripping (zero crossing tripping) [140].

Such challenges in DC systems also cause contact erosion of breakers resulting in a short lifetime and high maintenance cost of DC protective devices. To overcome the challenges of DC microgrid protection, the microgrid control system should be facilitated with fast and intelligent fault current limiting devices that can ease the protection system both in performance and cost reduction. Some of the related works in recent literature are compared with this study and tabulated in Table 2.12.

Table 2.12: Comparison of Related Works in Literature

Ref. No.	Year	Adopted Control Strategy	Load Variation & Switching	Set Point Parameters Upgradation	Fault Tolerance Capability
118	2020	Cascaded Master-slave	Yes	No	No
119	2019	Adoptive Control with Parameters Estimation	No	No	No
142	2019	Power Flow based Distributed Optimal Control	No	No	No
143	2022	Droop based Sliding Mode Control using Fuzzy Approximator	Yes	No	No

Table 2.12 continued

144	2020	Additional Reconfiguration Algorithm based Droop Control	Yes	Yes	No
145	2019	Adaptive Droop FCL based Droop Control	No	No	Limited Capability
This Study	2022	Circulation Current Minimization based Distributed Control	Yes	Yes	High Capability

2.10 Chapter Summary

This chapter has summarized the adverse effects of RES integration on microgrid stability, reliability, and PQ issues. Power intermittency, switching of power converters, protection system scheme, penetration level, and the location of RES are the key factors that contribute to such issues. The discussions in this chapter justified that DC microgrids with the LVDC distribution system can provide better control, low power losses, and better efficiency. However, DC microgrids and DC distribution systems still lack common standards in terms of domestic and commercial applications worldwide. Also, the cost-effective protection of DC systems has not been developed compared to AC protection systems. Thus, it can be concluded that the control and protection of DC microgrids and DC distribution systems are the key areas that future research should focus on to establish increased real-time application of the DC systems.

CHAPTER 3

TECHNO-ECONOMIC ANALYSIS

3.1 Introduction

Microgrid deployment is a suitable solution to integrate distributed renewable energy sources to meet the increasing load demands and to power up remote areas. The main challenge of implementing the DC microgrid is the existing structure of the AC distribution system. In addition to the previous research performed on DC microgrids, this study presents a simplified conceptual path toward various aspects of DC power transfer that could be generally applied to the existing AC distribution systems. To achieve this objective, the following factors shown in Figure 3.1 were considered for comparison as methodology.

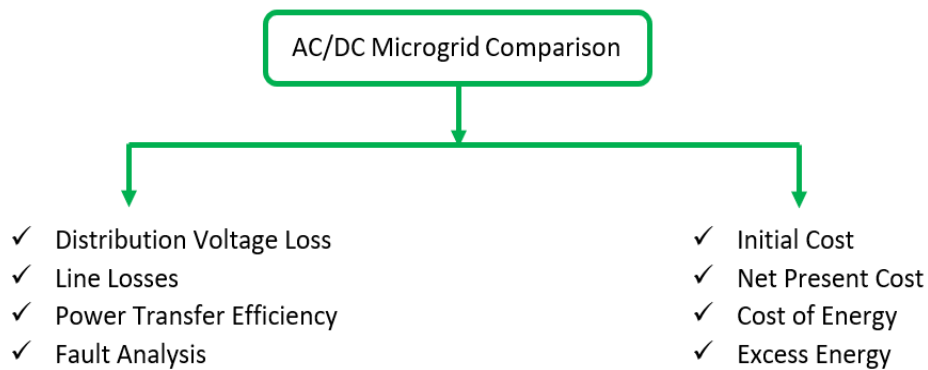


Figure 3.1: Factors Considered for Comparison

The feasibility of DC power transfer on the existing 230-volt AC network was analyzed and the impact of line voltage drop, power loss and efficiency of AC and DC microgrids during the steady-state conditions was compared. Furthermore, economic analysis has been carried out to determine the optimal size of solar PV system with its energy storage connected to each AC or DC microgrid in terms of workability, performance, and cost-effective power supply for off-grid communities.

3.2 Comparison of Losses and Efficiency

In this section, the technical comparison on the basis of voltage drop, power loss and energy efficiency of the microgrid system was evaluated using AC and DC power flow. For better understanding, Power losses due to skin effects and power conversions such as transformers in AC systems and power electronics converters. To make reasonable comparisons, two cases were considered for the microgrid under analysis: (i) DC voltage level equal to the root mean square (rms) value of AC quantities to transmit the same power. (ii) DC voltage level equal to the peak value of AC voltage, assuming a radial single-phase distribution system supplying a load of 5kW (kilowatt). The single line diagram is shown in Figure 3.2.

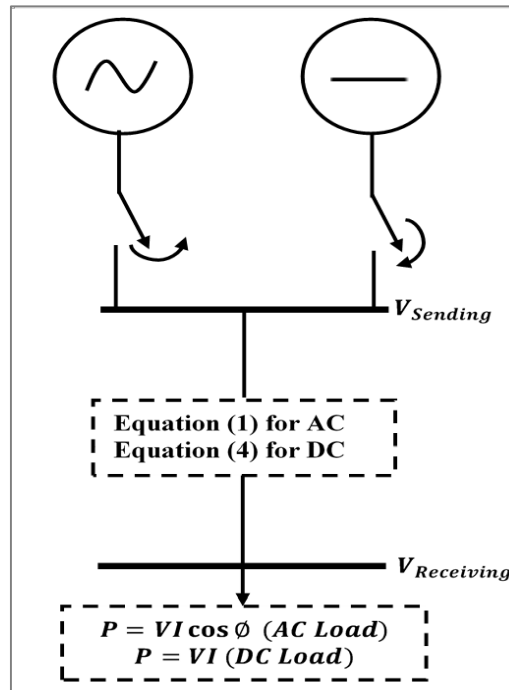


Figure 3.2: AC/DC Test System for Comparison

The conductor area (plain aluminum) of the overhead line with its Ohmic impedance was selected according to IEC 61089 standard [142]. The standard specifies the electrical and mechanical characteristics of round wire overhead electrical stranded conductors. The

voltage drop, line current, and power loss in the line using AC power flow were obtained by utilizing Equations 3.1 – 3.3, respectively.

$$V_{drop(AC)} = R_c I \cos \phi + X_c I \sin \phi \quad \text{Equation 3.1}$$

$$I_{AC(rms)} = \frac{P}{V_{rms} \times \cos \theta} \quad \text{Equation 3.2}$$

$$P_{Loss(AC)} = 2 \left(\frac{P^2}{V_{rms}^2 \times \cos^2 \theta} \right) R_c \quad \text{Equation 3.3}$$

The terms R_c , X_c , $I_{AC(rms)}$, V_{rms} , P , $P_{Loss(AC)}$ and $\cos \theta$ represent the conductor resistance, conductor reactance, line current, rms value of phase-voltage, transmitted power, power loss in the line and power factor (typically 0.85 [143]) of the system respectively. The factor “2” in Equation 3.3 is multiplied to calculate power loss in a pair of conductors for single phase distribution. In the case of low-voltage and low-power networks, conductor reactance (inductance and capacitance) is neglected for simplification of technical analysis because the IEC 61089 standard [142] describes the total resistance/impedance of line in ohms and the given value of impedance is used for calculation [80]. For a DC system, the line voltage drop, line current and power loss were found using Equations 3.4 – 3.6, respectively.

$$V_{drop(DC)} = R_c \times I \quad \text{Equation 3.4}$$

$$I_{DC} = \left(\frac{P}{V_{DC}} \right) \quad \text{Equation 3.5}$$

$$P_{Loss(DC)} = 2 \left(\frac{P^2}{V_{DC}^2} \right) R_c \quad \text{Equation 3.6}$$

Using Equations 3.3 and 3.6, the ratio of $P_{Loss(DC)}$ to $P_{Loss(AC)}$ is obtained as,

$$\frac{P_{Loss(DC)}}{P_{Loss(AC)}} = \frac{V_{rms}^2}{V_{DC}^2} \cos^2 \theta \quad \text{Equation 3.7}$$

According to the standard LVD 72/23/EEC, higher DC voltage ratings can be used compared to AC voltage ratings with the same conductor diameter which potentially increases the power transfer capacity [85].

Considering that $V_{DC} = \sqrt{2} V_{rms}$, Equation 3.7 can be rewritten as,

$$\frac{P_{Loss(DC)}}{P_{Loss(AC)}} = \frac{1}{2} \cos^2 \theta \quad \text{Equation 3.8}$$

Equations 3.1 - 3.6 were used for both cases (i and ii) as previously mentioned above to analyze the voltage drops and power losses in the line.

3.3 Comparison of Dynamic Behavior

Besides the wide potential of DC microgrids for different power applications, DC systems still lack universally adopted standards and cost-effective protection schemes due to the requirement of high power rating protective devices and are the significant obstacles to adopting DC systems on a large scale [22]. In particular, protection against short-circuit faults is the major challenge associated with DC microgrids due to higher magnitudes for fault currents. Therefore, the effect of short-circuit fault was analyzed by utilizing a stand-alone microgrid design for both AC and DC configurations to evaluate the system response against transient disturbances and faults. For this study, an array of 14 PV modules (Trina Solar TSM-250PA0.5.0) connected in series were utilized for power generation in both AC and DC microgrid with a maximum capacity of 3.5 kW connected to a 2kW resistive load. Each PV module generates an open-circuit voltage of 37.6v DC and a DC short-circuit current of 8.55amps at standard irradiance of $1000 \text{ Watt}/m^2$ and $25^\circ C$. The maximum power point tracking (MPPT) values of voltage (V_{mpp}) and current (I_{mpp}) are 31v and 8.06

amps respectively. The I-V and P-V characteristic curve of individual PV module is shown in Figure 3.3.

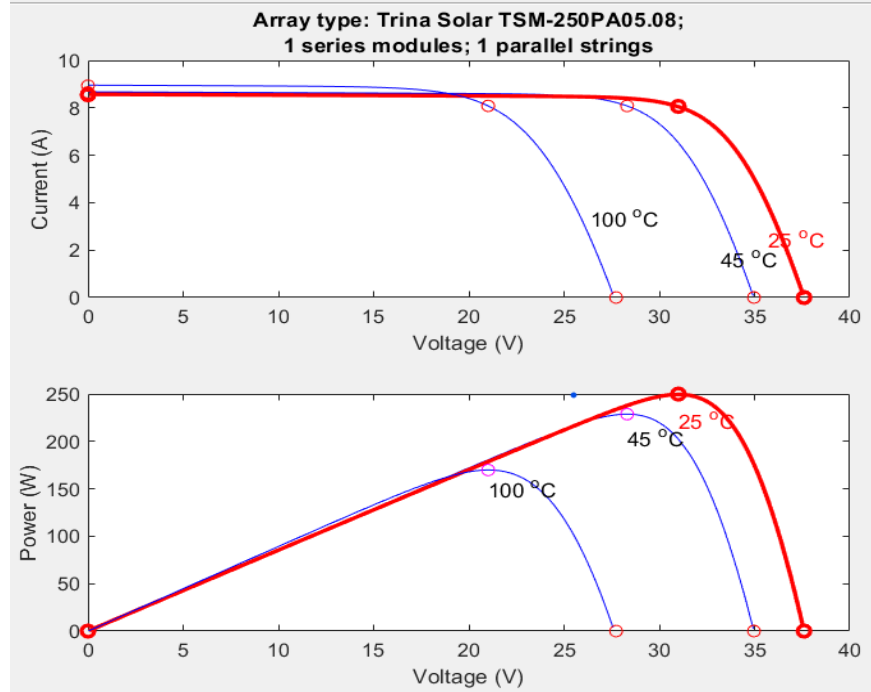


Figure 3.3: I-V and P-V Characteristic Curve of PV Modules

In the AC microgrid model shown in Figure 3.4, a DC/AC inverter (H-Bridge) is used to convert the DC power of PV array into AC power with its inverter control. The controller regulates the gate signal of DC/AC inverter based on the information obtained from the PV array to maintain the desired voltage levels. The DC/AC inverter control is based on phase locked loop (PLL), MPPT using a perturb & observe algorithm, DC voltage regulator, current regulator, pulse width modulation (PWM) modulator, and Measurements. An RLC filter is also used at the output of DC/AC inverter to filter out the ripples and unwanted the AC harmonics from AC bus voltage.

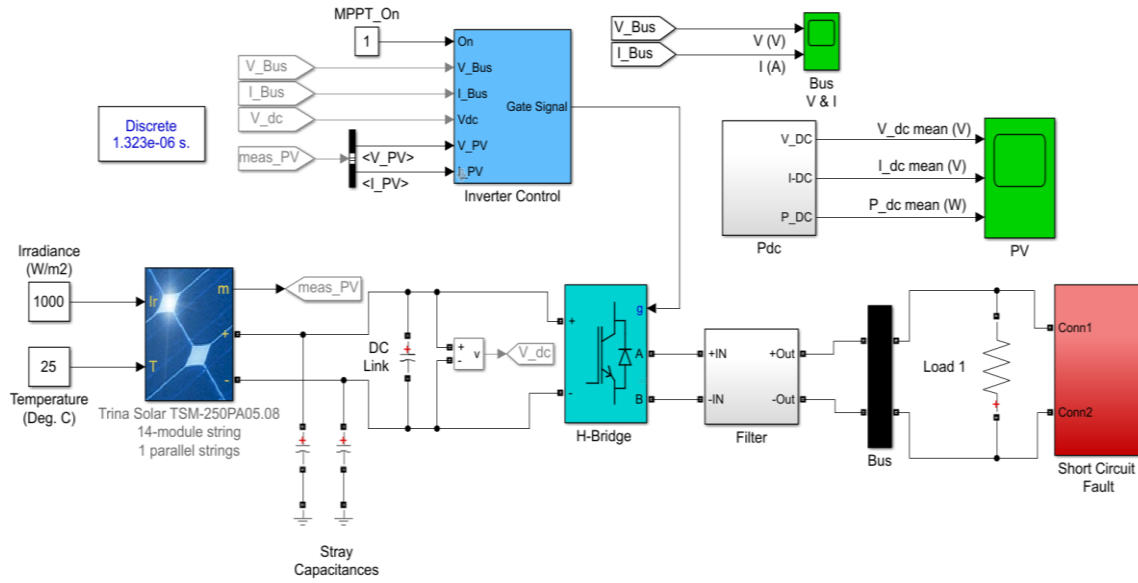


Figure 3.4: Simulink Model for Short-circuit Fault Analysis in AC Microgrid

In the DC microgrid model shown in Figure 3.5, a DC/DC converter is used to maintain the PV array voltage at the desired level using MPPT technique using a perturb & observe algorithm.

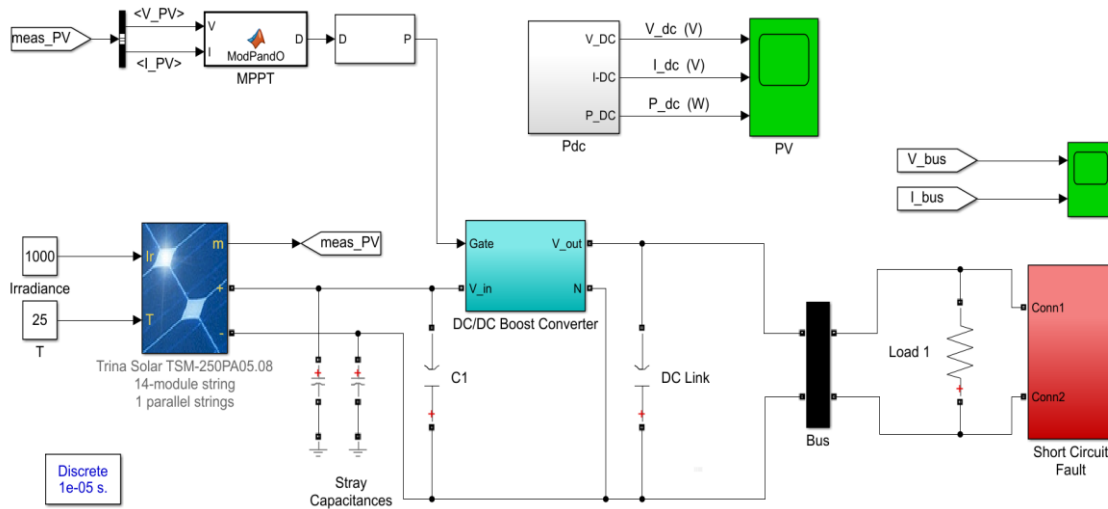


Figure 3.5: Simulink Model for Short-circuit Fault Analysis in DC Microgrid

As discussed above, the domestic AC voltage magnitude of 230v was supplied from AC and DC microgrid systems to a residential load. A small duration (200ms) short-circuit

fault was introduced across the load terminals and cleared for analyzing the response of AC and DC microgrid. As the protection of DC microgrid is out of the scope of this study, it was assumed that efficient protection and fault isolation schemes exist in the system.

3.4 Economic Analysis

Economic analysis is a key factor that should be considered while designing the DC or AC microgrid. In the designing stage of a microgrid, proper sizing of the DRG and ESS is crucial as it plays an important role in determining the total net present cost (NPC) of the system over its lifetime, the average cost of energy (COE), and energy efficiency. The sizes of solar PV and ESS depend on the solar radiation available and energy usage pattern/load profile. For this study, a remote village community in Bario (3°44.1'N, 115°28.8'E), Sarawak (Malaysia) was identified to find out the solar profile data. Bario is located on mountainous terrain (178 km to the east of Miri at an altitude of 1000 m above sea level) and comprises of 13 to 16 remote villages with lower power demands. Hence, it is not feasible to be connected with the Sarawak grid [140]. In this work, a stand-alone microgrid model was formulated by considering different sizes of components to find the optimal configuration. Here, the optimal configuration was determined by minimizing the total NPC in Equation 3.9 which represents the difference between the total costs of the system (as listed below) and the revenue of the project that it earns over the lifetime of the system [145], [146]..

- i. The cost of PV panel, battery, and power converter.
- ii. The cost of operation (including the maintenance cost) throughout the project's lifetime.
- iii. The replacement cost of the components throughout the life of the project.

$$\min(\sum TCS - PR) = \sum NPC = \frac{C_{t(annual)}}{CRF(i,Y)} \quad \text{Equation 3.9}$$

where TCS , PR , $C_{t(annual)}$ and CRF represent the total cost of the system, project revenue, total annual cost and capital recovery factor respectively. The terms i and Y are the interest rate and the project lifetime (25 years) respectively. The CRF can be found using Equation 3.10.

$$CRF(i, Y) = \frac{i(i+1)^Y}{(i+1)^Y - 1} \quad \text{Equation 3.10}$$

For solving the optimization problem given in Equation 3.9, the load following dispatch approach was implemented to meet the load demand using the hybrid optimization model for electric renewable (HOMER), aiming to find the optimal configuration that has the lowest NPC. In other words, this tool models the physical behavior of the microgrid and calculates its NPC including installation, operation, and maintenance costs of the system over its life span. As the main objective of this paper was to assess the technical and financial benefits of AC and DC microgrids based on the solar PV system, the optimization strategy considers only one source (PV) in the stand-alone microgrid. Here, it was assumed that the system operates in different modes according to the climate conditions. When solar irradiation is available, the control system prioritizes the PV panels to supply the loads. Under this condition, any further excess energy should be either utilized for the charging process or dumped. However, if there is less energy output from the PV panels, the battery will supply the load until the state of charge (SOC) reaches its minimum level (60%) as given in Equation 3.11.

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad \text{Equation 3.11}$$

The decisions of the control system to operate the energy component and to charge or discharge the batteries take place on an hourly basis and are based on the energy balance computation as expressed in Equation 3.12.

$$P_{PV}(t) + P_{ES}(t) = P_L(t) + P_{LO}(t) \quad \text{Equation 3.12}$$

where $P_{PV}(t)$, $P_{ES}(t)$, $P_L(t)$ and $P_{LO}(t)$ are solar PV output power, the power from energy storage, the load demand and power loss respectively.

The solar radiation data for the specific area (Bario, Sarawak) and the hourly load profile of the served area with their costs, electricity tariff and constraints of the system were taken as inputs and an hourly energy balance calculation is performed for the whole year. Constraints refer to a set of conditions the microgrid system must satisfy and are used as input to optimize the size of power resources such as PV and batteries to ensure reliable power supply to the load during all conditions. Constraints define the required amount of surplus operating capacity (operating reserve) for a sudden increase in load or decrease in RES output power. The HOMER optimization algorithm records any shortfall as a capacity shortage and varies the capacity of power units to keep the operating reserve greater than or equal to the required operating reserve. In this study, the constraints are the meteorological data (variation in solar irradiance due to weather conditions, temperature, daytime, and weather forecast obtained from NASA for a particular area), and the load profile of Bario.

Generally, scaled data is used for HOMER optimizer calculations to perform sensitivity analysis on the load profile or for unit conversion (from W to KW). To generate scaled data for the optimization process, each value of the baseline data is multiplied by a common factor. As a result, scaled annual average data retain the same statistical

characteristics of the baseline data but may differ in magnitude. The load profile and scaled annual average (SAA) with a load factor of 0.52 are shown in Figure 3.6 (a, b).

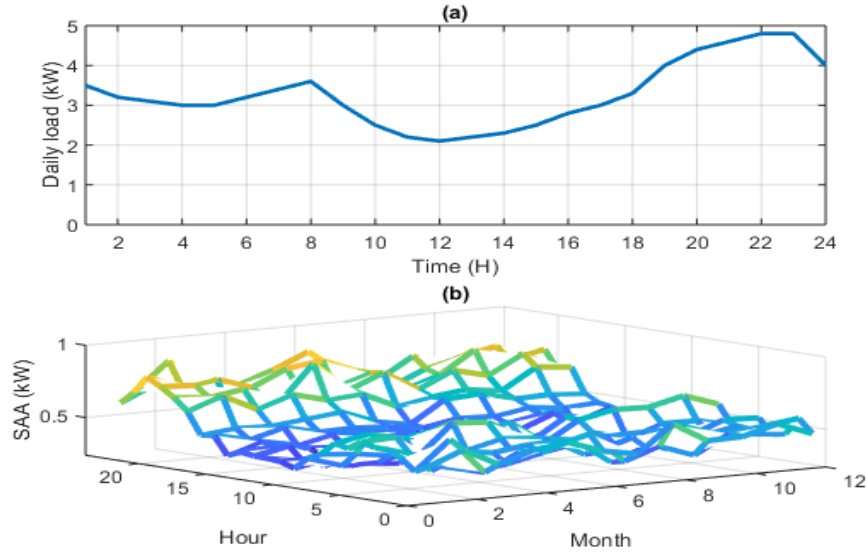


Figure 3.6: (a) Daily Load Profile; (b) Scaled Annual Average

Various atmospheric components (such as gas molecules, clouds reflectivity, aerosols, pollen, haze, and smoke) scatter or absorb the intensity of extraterrestrial radiation from the sun and attenuate the global solar radiation as it propagates through the atmosphere and reaches the Earth's surface. The fraction of extraterrestrial radiation that reaches the Earth's surface is called the clearness index and is a key factor in quantifying and determining the global solar radiation received at any location using meteorological data of that area. Theoretically, its value varies from 0 to 1 (usually about 0.8 in clear sky and near 0.2 in cloudy conditions) depending upon the weather conditions and indicates the availability of solar radiation at any location. Knowing the clearness index value of a particular area is crucial to evaluating the climatological potential and the utilization of solar energy [147]. HOMER optimizer calculates the monthly average clearness index using average solar radiation, the month of the year, and the latitude of a specific location. The average solar radiation with the clearance index for Barrio is depicted in Figure 3.7.

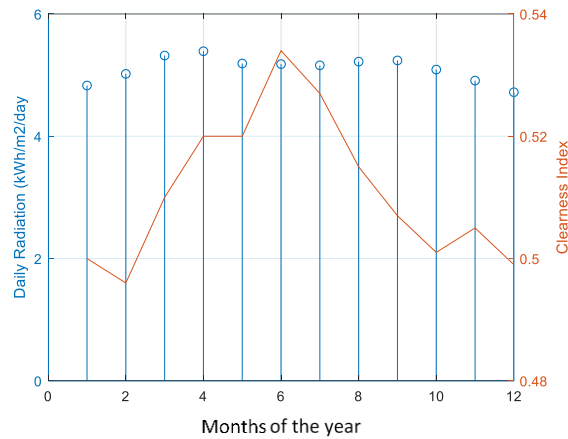


Figure 3.7: Average Solar Radiation and Clearance Index for Barrio

The general inputs for microgrid optimization in HOMER are given in Table 3.1 [145], [146].

Table 3.1: Inputs Required for HOMER Optimization

Input	Details
Meteorological Data	Solar radiation, clearness index, temperature, and latitude of the Specific Location.
Component Characteristics	I-V and P-V characteristics of PV modules, Efficiency of inverter and battery storage,
Load Profile	Power demand of connected load at specific time
Economic Data	Capital, replacements and maintenance costs of each equipment needed to calculate the NPC of each configuration
Controller	Technical data such as system constrains and dispatch strategy
Search Space	Variety in sizing each component for the optimization approach

Cost minimization in Equation 3.9 is dependent on the power balance (Equation 3.12) at time “ t ” and state of charge limits (Equation 3.11). The overall modeling approach implemented to optimize Equation 3.9 is simplified in Figure 3.8.

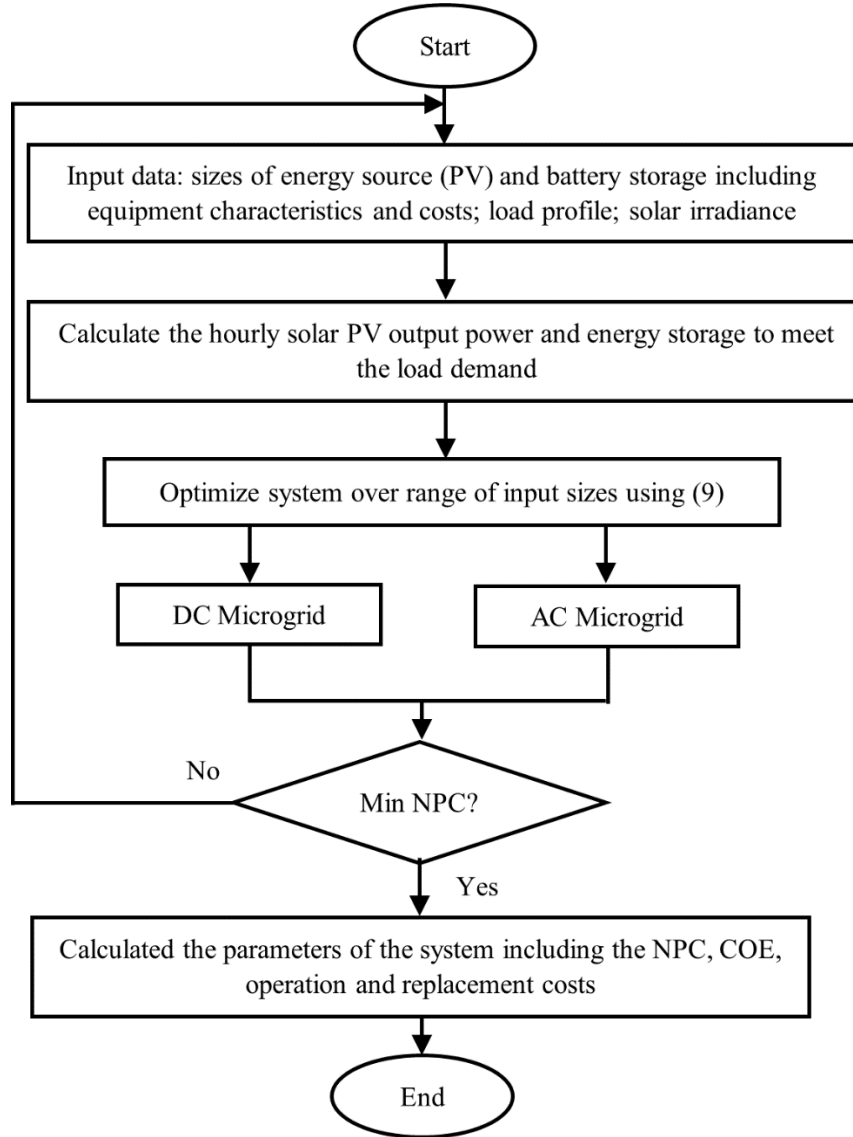


Figure 3.8: Flowchart Simplifying the Optimization Procedures of Microgrid

Referring to Figure 3.8, initially, the sizes of the solar PV system and battery storage that can efficiently meet the load demand were identified with the solar radiation profile of the specific area. The equipment characteristics (solar PV system and battery storage) including the converter with their costs were taken into account as well in the initialization

step. Note that the hourly solar PV output power and energy storage were calculated based on the hourly solar irradiance. In the second stage (optimization stage), different combinations of system configuration for the AC and DC microgrids (shown in Figure 3.9 (a, b, c)) were tested to find out the lowest NPC of the microgrid subject to the constraints (power balance and technical characteristic).

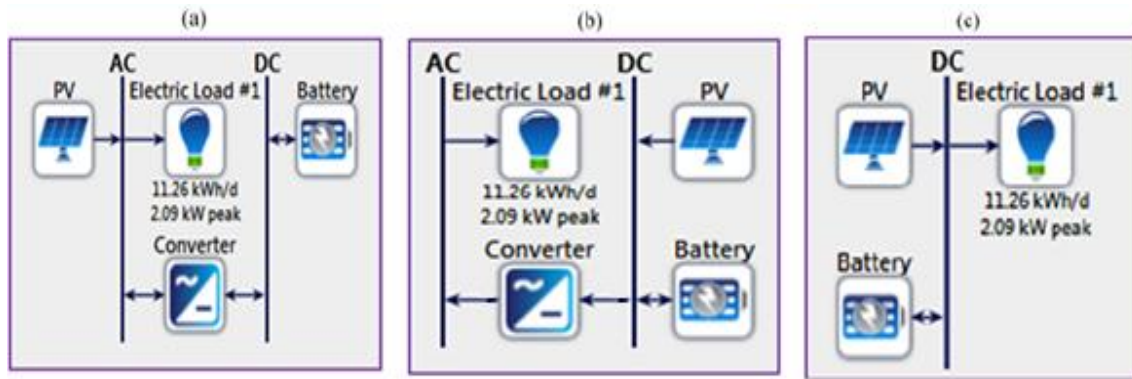


Figure 3.9: Microgrid Configurations; (a) AC Source and AC Load (b) DC Source and AC Load (c) DC Source and DC Load

Figure 3.9 (a) shows an AC microgrid configuration where the solar PV modules are connected to the AC bus using internal DC/AC inverter to supply the AC load while the battery storage is connected to AC bus by utilizing a bidirectional AC/DC/AC converter between AC and DC buses. The internal PV inverter and converter used for the battery are not displayed in HOMER for better understating of the system. However, their relative efficiency and cost is included in the calculation for the optimal solution. Figure 3.9(b) also presents an AC microgrid configuration, however, the PV modules and batteries are connected to the DC bus while the AC load is supplied by utilizing a DC/AC converter. Figure 3.9(c) represents the pure DC microgrid configuration where the PV modules, battery storage and DC load are connected to the same DC bus.

The output of the optimization stage (Min NPC) that satisfies Equation 3.9 enables obtaining the system parameters including the NPC, COE, operation, and replacement costs. Generic flat plate PV of 1kW rated capacity was selected with a derating factor assumed to be 0.8 in order to include the effect of temperature, dust, and wire losses. The output power of PV was calculated using Equation 3.13, where D is the derating factor, $P_{PV(rated)}$ is the rated capacity of PV at standard test conditions (1kW/m² and 25°C), I is the solar radiation incident on the surface of the PV and I_s is standard radiation incident (1kW/ m²).

$$P_{PV} = D \times P_{PV(rated)} \left(\frac{I}{I_s} \right) \quad \text{Equation 3.13}$$

The maximum power point tracker was assumed to be present in the system to neglect the effects of voltage. The generic equation of hourly energy output at time “ t ” for each PV is given by Equation 3.14, where p is the PV penetration level factor; A_{PV} denotes the surface area m²; $g(t)$ is the hourly irradiance kWh/m²; η_{PV} represents the efficiency of PV panel.

$$E_{PV}(t) = pA_{PV}g(t)\eta_{PV} \quad \text{Equation 3.14}$$

The energy stored in a battery bank (collection of individual batteries) at time “ t ” is the cumulative sum of the daily charging and discharging rates. The cumulative energy storage was calculated using Equation 3.15, while the battery bank lifetime limited by throughput and time was obtained using Equation 3.16. Here, $E_{cc}(t)$ is the energy from the charge controller; η_{ch} is the charge efficiency of the battery bank in kWh; n , Q_{lt} , Q_{ath} and L_f are the number of units in the battery bank, the lifetime throughput of battery bank (kWh), the annual throughput of battery bank (kWh/year) and the float life of battery bank (year) respectively.

$$E_{ESS}(t) = E_{ESS}(t - 1) - E_{cc}(t)\eta_{ch} \quad \text{Equation 3.15}$$

$$BB_{LT} = \min\left(\frac{nQ_{lt}}{Q_{ath}}, R_f\right) \quad \text{Equation 3.16}$$

Equation 3.17 gives the annual cost of all components in each configuration.

$$C_{t(annual)} = \sum_{pv=1}^{n_{pv}} (PV_{acc} + PV_{aoc} + PV_{arc}) + \sum_{c=1}^{n_c} (C_{acc} + C_{aoc} + C_{arc}) + \sum_{b=1}^{n_b} (B_{acc} + B_{aoc} + B_{arc}) \quad \text{Equation 3.17}$$

where, PV_{acc} , PV_{aoc} , PV_{arc} , C_{acc} , C_{aoc} , C_{arc} , B_{acc} , B_{aoc} , B_{arc} are the annual capital, operational and replacement costs of the PV panels, converters and batteries respectively; n_{pv} , n_c and n_b are the numbers of PV panels, converters and batteries respectively. The COE was determined for the considered configurations using Equation 3.18, where E_{served} is the total annual load served kWh/year.

$$COE = \frac{C_{t(annual)}}{E_{served}} \quad \text{Equation 3.18}$$

As each configuration has only one source with energy storage, the considered dispatch strategy is based on load following as in Equation 3.19. This means that the solar PV should first meet the load requirement, and then, the surplus power from the solar PV can be used to charge the battery bank.

$$P_{PV}(t) = P_L(t) + P_{LO}(t) + P_{ES}(t) \begin{cases} PV \text{ output} > 0 \\ SOC < 100\% \end{cases} \quad \text{Equation 3.19}$$

3.5 Results and Discussion

This section presents and discusses the results obtained from the technical and economic assessment of different AC and DC microgrid configurations as discussed in Section 3.2.

3.5.1 Results of Technical Analysis

This section discusses the results of power line losses, percentages of voltage drop and system efficiency for AC and DC microgrids obtained using MATLAB code for equations from the technical analysis are shown in Figures 3.10 (a, b, c) respectively.

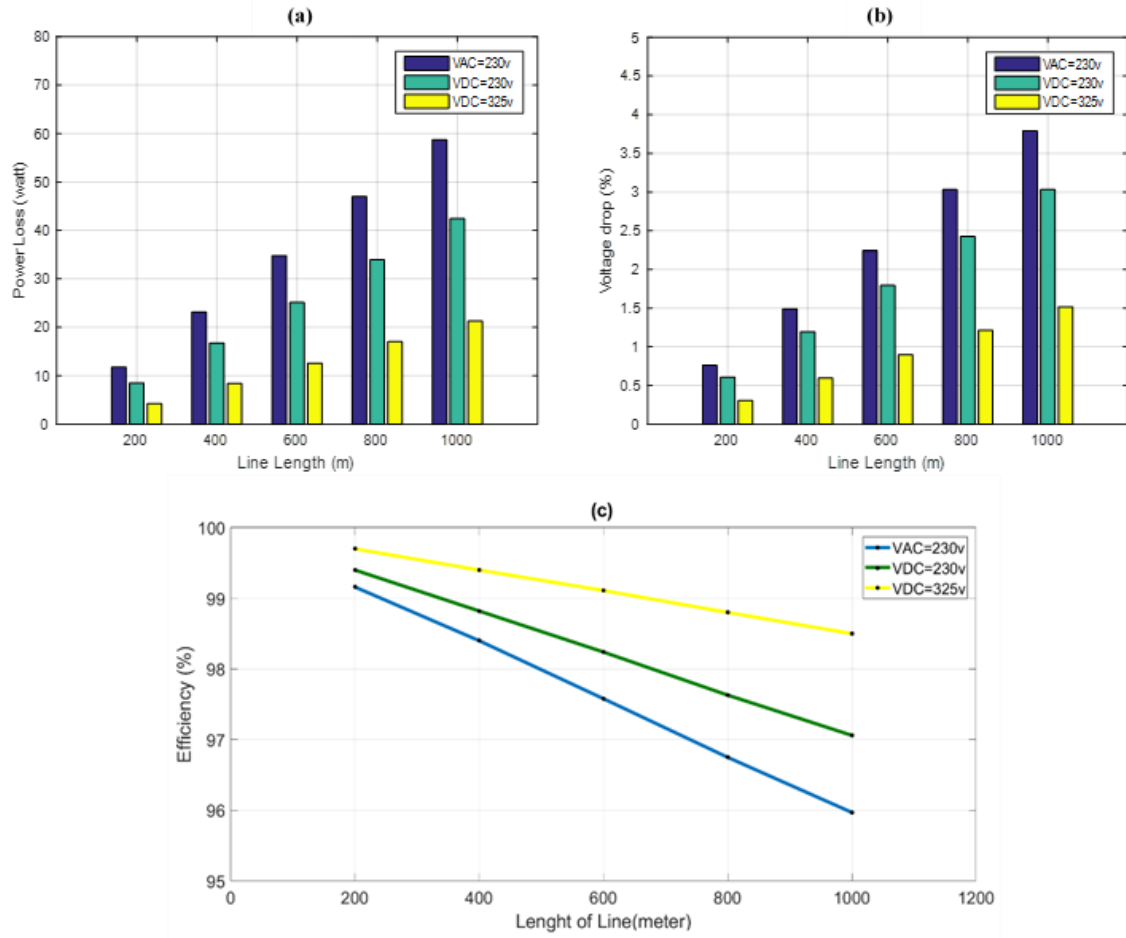


Figure 3.10: Comparison of AC and DC Distribution Systems; (a) Power Loss, (b) Voltage Drop (c) Efficiency

As seen in Figure 3.10 (a), the power loss in the AC distribution system is higher than the DC distribution for the same voltage level and supplied load power. It can also be observed from Figure 3.10 (b) that the voltage drop in the distribution system of an AC microgrid is higher than the DC microgrid while supplying the same amount of load power. The reason is the additional reactive power loss component due to which reactive current

flows in the line. Referring to the second case as explained in Section 3.2, when the DC voltage level is considered equal to the peak value of AC voltage (i.e., $V=325\text{V}$), the power loss becomes half compared to the AC microgrid. It is also seen in Figure 3.10 (c) that the efficiency increases when the voltage level of the DC system is higher. In other words, the DC microgrid will have the lowest power loss while transmitting the same amount of power using the same line length and conductor characteristics. In the long distribution AC lines, power line loss becomes more significant causing higher voltage regulation issues.

3.5.2 Results of Dynamic Behavior Comparison

To analyze the level of impact due to a fault on the AC and DC microgrid, a short-circuit fault was introduced in each microgrid configuration. The effects of short-circuit faults on the voltage and current in AC and DC systems are shown in Figure 3.11 (a and b).

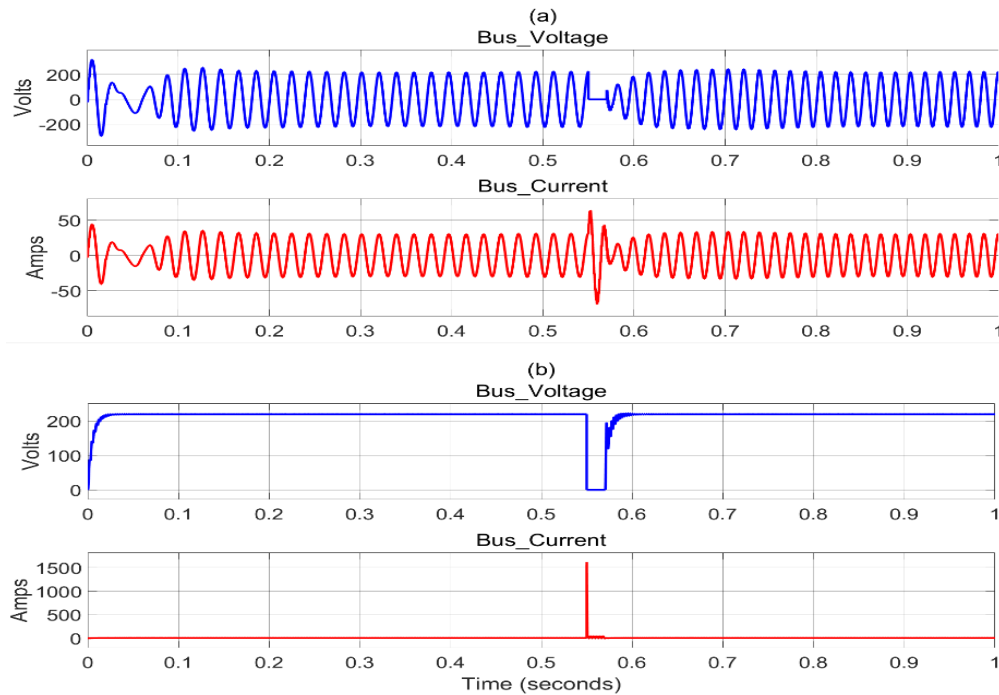


Figure 3.11: Impact of Short-circuit Fault on; (a) AC Microgrid (b) DC Microgrid

It can be noticed from Figure 3.11 (b) that the value of fault current in DC microgrid is much higher as compared to the AC microgrid (see Figure 3.11 (a)). This affirms the fact

that short-circuit fault currents in DC system have much higher magnitudes than AC while the settling time for AC (0.08 sec) is more than DC (0.04 sec). Therefore, efficient fault current limiting technologies are needed to prevent considerable damage to the microgrid equipment. For the purpose of simplicity, the DC voltage level was taken equal to the peak value of AC voltage which results in lower DC current and fewer losses while supplying the same load as discussed in Section 3.2.

3.5.3 Results of Economic Analysis

This section demonstrates the results of financial benefits that can be gained due to the installation of DC microgrid instead of AC microgrid. The HOMER optimizer evaluates the best optimal solutions on an hourly basis using the meteorological data of a specific location for the whole year. This is because of the continuous variation in the climate conditions (such as clearness index, solar radiation, temperature, etc.) and load demand at that specific time. The hourly load demand is already shown in Figure 3.6(a) while the power generated from solar PV, total electrical load supplied and state of charge (SOC) of the battery storage for a specific duration (1st Jan to 19th Jan) are shown in Figure 3.12.

It can be seen from the above figure that during the daytime solar PV generates power to supply the load as well as charge the battery storage. The variation in total generated PV power on different days depends on the solar radiation, temp, etc. The SOC of battery storage increases when PV is generating power and decreases while supplying load at nighttime. Using the HOMER optimizer, the best optimal solutions for all three microgrid configurations were analyzed for economic comparison as discussed in section 3.4. Although a variety of calculations and results are generated by the HOMER optimizer, the most significant factors are considered and tabulated in Tables 3.2 and 3.3.

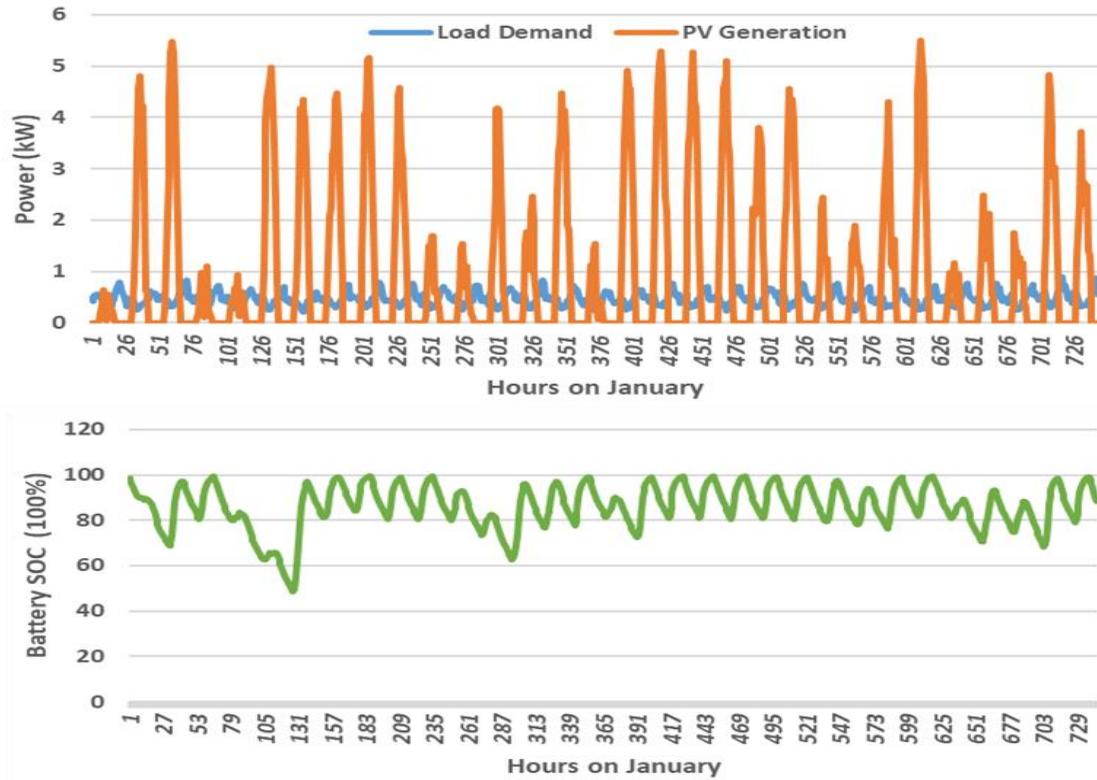


Figure 3.12: PV Power, Load Demand and SOC of battery Storage

Table 3.2: Comparison of Microgrid Configurations

Case Study	MG Configuration		PV Capacity (KW)	No. of Battery Units	Net Present Cost (\$)	Cost of Energy (\$ per kwh)	Operating Cost (\$/yr)	Initial Capital Cost (\$)	Excess Electricity (kwh)
	PV	Load							
A	AC	AC	7.44	38	49050	0.924	1143	34281	5639
B	DC	AC	7.46	38	48776	0.919	1136	34088	5753
C	DC	DC	5.91	43	46792	0.882	1251	30619	3761

It was observed from Table 3.2 that the lowest cost of the system is achieved when the configuration (Figure 3.9 c) of the microgrid contains DC load and DC generation.

Compared to other configurations (Figure 3.9 a) when the PV contains an inverter connected to AC load and (Figure 3.9 b) when DC generation is connected to AC load through the bidirectional converter; the DC load with DC generation is the cheaper configuration that can operate with less excess electricity. Table 3.3 summarizes the results of conversion losses and usable energy for three case studies. The key technical parameters as shown in this table are characterizing the performances of ESS and converting system.

Table 3.3: Comparison of Important Technincal Parameters

Parameters	Microgrid Configuration		
	Case A	Case B	Case C
Total Conversion Loss (kWh/yr)	979	887	644
Annual Throughput of Energy Storage (kWh/yr)	2994	3002	2883
Usable Nominal Capacity of Energy (kWh)	22.8	22.8	25.8

The results in Table 3.3 clearly indicate that the DC microgrid will have the maximum lifespan. Furthermore, the utilization of the DC microgrid system reduces the conversion losses, as the inverter and converter are not used. It was also seen from Table 3.3 that due to the lower energy consumption of DC appliances, the usable capacity of energy storage increases in the DC microgrid (see case C).

3.6 Chapter Summary

In this chapter, a framework to assess the technical and financial benefits of the AC and DC microgrids has been presented. It has been revealed that DC microgrid can improve system efficiency with the same distribution infrastructure used in the AC microgrid. The

results show that applying DC voltage equal to the peak value of an AC waveform reduces the power loss by up to the half value compared to an AC microgrid. Additionally, the voltage drop in the distribution lines was reduced by 29.3%. Though DC systems are much simpler in operation and can eliminate different issues such as synchronization (voltage and frequency control), the obtained results of the dynamic analysis indicate that stability issues during disturbances require careful attention when designing the DC microgrid. Accordingly, the next Chapters (4 and 5) address the voltage regulation and stability of voltage during fault conditions in order to maintain acceptable voltages in the DC microgrids and desired power sharing. From an economic point of view, the results established the fact that a DC microgrid with a PV-battery system is affordable and cheaper than the conventional AC microgrid, as the inverter is not needed in the DC microgrid which in turn reduces the conversion stages and the overall cost of the system. Therefore, it is expected that the installation of the DC microgrid can be an optimal option for large-scale renewable energy integration and electrification of the transportation sector. Finally, the framework presented in this study is based on a generic optimization method which can be an effective scheme for the implementation in other related works.

CHAPTER 4

POWER SHARING AND VOLTAGE REGULATION

4.1 Introduction

The key operational issues in DC microgrids are to ensure a stable output voltage and proper load sharing among the power sources. Further, in an islanded DC microgrid, load or source switching can also degrade power sharing and voltage regulation. To achieve this objective, the following methodology was adopted. To smooth the DC microgrid voltage and maintain the desired power sharing, a distributed secondary control strategy is developed based on average current/voltage control and circulating current minimization method. Moreover, to minimize the line voltage drop and power losses, an additional current feedback loop was introduced to modify the microgrid reference voltage during overload conditions. The conventional communication links were assumed for exchanging information with the relevant controllers to implement the proposed distributed control. The performance of the proposed approach is verified by simulating two parallel Buck converters supplying a common load and was compared with the traditional droop control method. The effect of load switching on voltage regulation and power sharing is also analyzed.

4.2 Voltage Control and Load Power Sharing

The output voltage fluctuations of power converters and mismatches between line resistances of different sources can degrade the power sharing accuracy and voltage regulation in DC microgrids. The traditional droop control provides better current sharing in DC microgrids; however, droop control imposes a voltage drop due to the presence of droop resistances. The value of droop resistance is directly proportional to the current sharing accuracy of droop control. Therefore, higher droop resistance will impose more voltage

deviations in the output voltage. Moreover, high voltage deviations may take place due to the high load currents or mismatch between line resistances. To enhance the voltage stability of the DC microgrid, such voltage deviations should be eliminated [143].

To date, various control approaches are reported in the literature as discussed in Section 2.7. Generally, a three-level hierarchical control architecture has been developed for standardized operation and better functionality of microgrids. Power sharing and rapid voltage stabilization are ensured at the primary level of this hierarchical control. The secondary control compensates for the steady state voltage deviations imposed by the primary control [106], [110]. Another drawback of the conventional droop control is that the output voltage is linearly reduced with increasing output current, which induces a voltage deviation at the local and common DC buses compared to their rated values. Meanwhile, load distribution is influenced by the asymmetry of line impedances. By exchanging information via communication links, distributed secondary control is capable of adjusting the set-points of primary control to provide further voltage regulation under fast-changing load conditions [144].

4.3 Circulating Current Issues

As discussed in the above section, the droop and line resistances influence the output voltage, a slight variation in output voltages of different power converters causes circulating currents in the microgrid system. The single line diagram of the test system as shown in Figure 4.1 represents the concept of power sharing between two DC microgrids located at different locations and connected in a radial fashion.

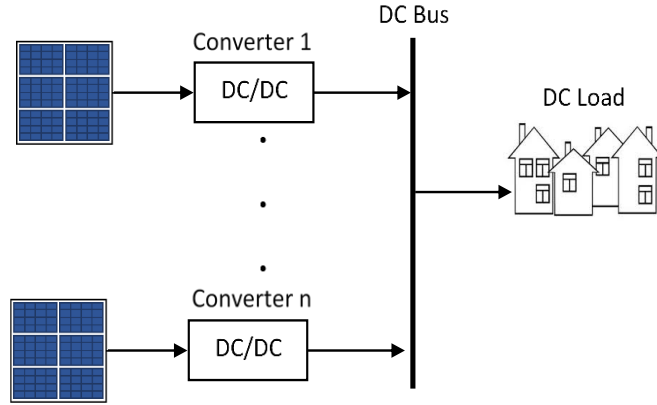


Figure 4.1: Test System for Power Sharing in a DC Microgrids

The solar PV arrays of different power capacities are connected in parallel with a DC bus through DC-DC power converters to supply a common load. Figure 4.2 shows the equivalent circuit of the test system given in Figure 4.1. In this circuit, R_L denotes a common DC load; V_1 , V_2 , I_1 and I_2 are the output voltages and currents of converter 1 and 2 respectively. Similarly, V_L and I_L are the load voltage and load current; R_{L1} and R_{L2} are the resistances of each line from converter 1 and 2 toward the load, respectively.

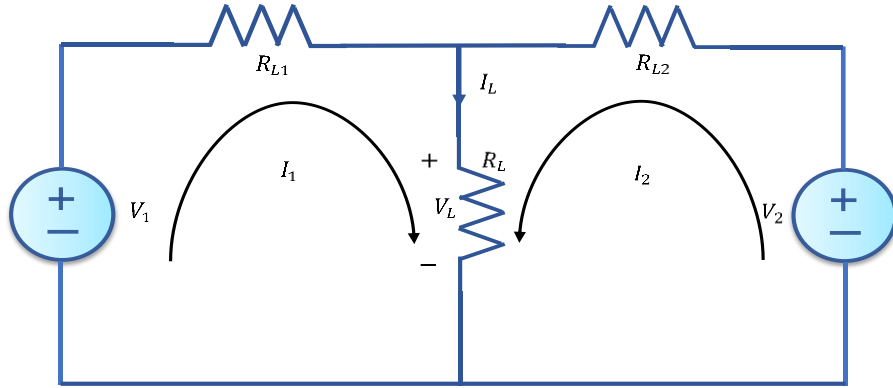


Figure 4.2: Equivalent Circuit of Parallel Connected Power Converters

Applying Kirchhoff's voltage law, Equations 4.1 and 4.2 are obtained,

$$V_1 = I_1 R_{L1} + I_L R_{Load} \quad \text{Equation 4.1}$$

$$V_2 = I_2 R_{L2} + I_L R_{Load} \quad \text{Equation 4.2}$$

The reference output voltage V_{ref} for both converters in the presence of droop resistances (R_{d1} and R_{d2}) for current sharing and voltage regulation is given by Equations 4.3 and 4.4.

$$V_{ref} = V_1 + I_1 R_{d1} \quad \text{Equation 4.3}$$

$$V_{ref} = V_2 + I_2 R_{d2} \quad \text{Equation 4.4}$$

Equations 4.1 – 4.4 show that the line and droop resistances influence the output voltage of the converter. Likewise, the output voltage is affected by a change in load or output power of the parallel converters, which generates circulating currents between converters. Hence, the magnitude of circulating current (I_{cir}) for the circuit in Figure 4.2 can be written as in Equation 4.5.

$$I_{cir1} = -I_{cir2} = \frac{V_1 - V_2}{R_{L1} + R_{L2}} \quad \text{Equation 4.5}$$

4.4 Converter Modeling and Control Approach

This section presents the mathematical model of the DC-DC buck converter and the voltage loop design of the converter output voltage controller. The current control loops for inductor current using a Proportional Integral (PI) control mode are also outlined. In the next stage, the proposed improved coordinated voltage control with the power sharing strategy is explained including the tapping function of voltage regulation in a microgrid system.

4.4.1 Converter Modeling

The buck converter circuit configuration is shown in Figure 4.3, where V_{in} and V_0 represent the input and output voltages of the converter, V_c represents capacitor voltage and I_L represents inductor current.

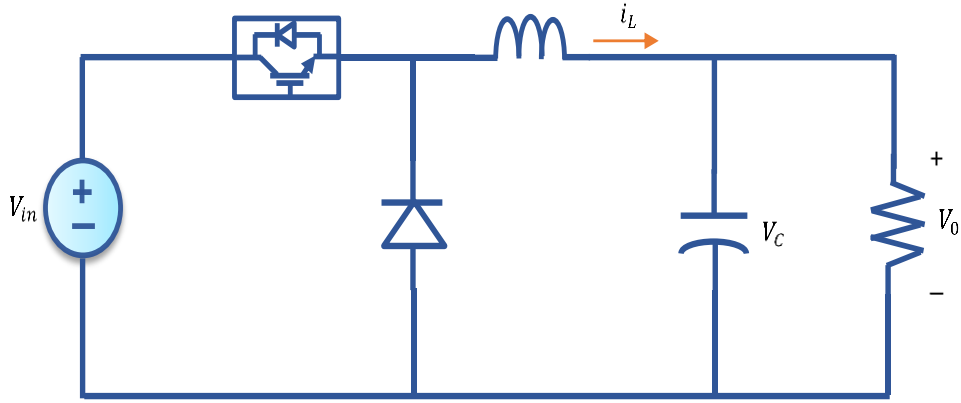


Figure 4.3: Buck Converter Configuration

The voltage conversion ratio of the buck converter depends on its duty cycle “ D ” as given by Equation 4.6.

$$D = \frac{V_o}{V_{in}} \quad \text{Equation 4.6}$$

Referring to Figure 4.3, the values of the inductor and capacitor can be found using Equation 4.7 and 4.8 respectively.

$$L = \frac{(V_{in} - V_o)D}{2\Delta i_L f_s} \quad \text{Equation 4.7}$$

$$C = \frac{\Delta i_L}{8\Delta V_o f_s} \quad \text{Equation 4.8}$$

where Δi_L and ΔV_o are the desired peak ripple of the inductor current and output voltage respectively; f_s is the switching frequency of the buck converter.

For small signal analysis, the linearized equivalent circuit of a buck converter is drawn in Figure 4.4. Here, R_{ind} is the internal resistance of the inductor while R_{cap} is the internal resistance of the capacitor.

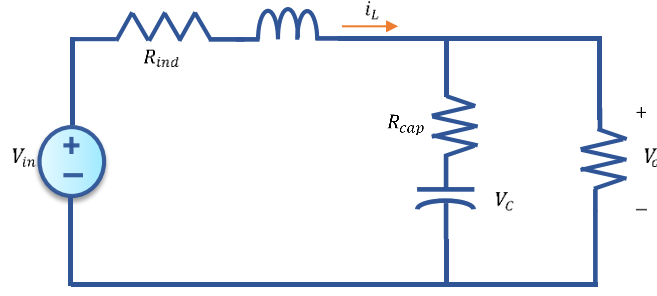


Figure 4.4: Linearized Equivalent Circuit of Buck Converter

The mathematical model of buck converter is simplified by Equations 4.9 and 4.10, where d , $i_L(t)$, $i_C(t)$, $V_C(t)$, and $V_o(t)$ are small variations around the predefined operating values for the duty cycle, the inductor current, capacitor current, capacitor voltage, and output voltage respectively.

$$i_C(t) = C \frac{dV_C(t)}{dt} = i_L(t) - \frac{V_o(t)}{R_{Load}} \quad \text{Equation 4.9}$$

$$L \frac{di_L}{dt} = V_{in} - i_L(t)R_{ind} - V_o(t) \quad \text{Equation 4.10}$$

To offer good decoupling for DC values, the capacitor value should be large enough. By transforming Equations 4.9 and 4.10 to the s -domain, the transfer function of the duty cycle to inductor current and the transfer function of inductor current to the output voltage can be written as,

$$G_{vi}(s) = \frac{V_o(s)}{i_L(s)} = \frac{1+sCR_{cap}}{sC} \quad \text{Equation 4.11}$$

$$G_{id}(s) = \frac{i_L(s)}{d} = \frac{v_{in}}{sL+R_{ind}} \quad \text{Equation 4.12}$$

4.4.2 Proposed Power Sharing and Voltage Control

To avoid instability in the primary control, the current control loop must be faster than the voltage control loop. The form of both current and voltage PI controllers ($C_i(s)$ and $C_v(s)$) is given by Equation 4.13, where K_p is the proportional gain term and K_I is the integral term.

$$C(s) = K_p + \frac{K_I}{s} \quad \text{Equation 4.13}$$

The transfer functions of the current controller $P_i(s)$ and voltage controller $P_v(s)$ are obtained utilizing Equations 4.14 and 4.15 respectively, where the term ' T_m ' represents the pulse width modulation (PWM) stage.

$$P_i(s) = T_m \times G_{id}(s) \quad \text{Equation 4.14}$$

$$P_v(s) = \frac{C_i(s) P_i(s)}{1 + C_i(s) P_i(s)} \times G_{vi}(s) \quad \text{Equation 4.15}$$

Referring to Equations 4.6 – 4.12, the duty cycle D is produced by the PWM stage that is proportional to the control voltage V_C . This value " V_C " is compared with a saw tooth waveform by the pulse width modulator. The peak-to-peak amplitude V_M of the sawtooth waveform is selected by the designer. Accordingly, the desired switching frequency of the converter f_s corresponds to the frequency of sawtooth waveform, which determines the switching (on/off) of the converter's MOSFET and thus, Equation 4.16 can be used to model the transfer function of the PWM stage.

$$T_m = \frac{1}{V_M} \quad \text{Equation 4.16}$$

The inner current and voltage loops of the primary control are shown in Figure 4.5.

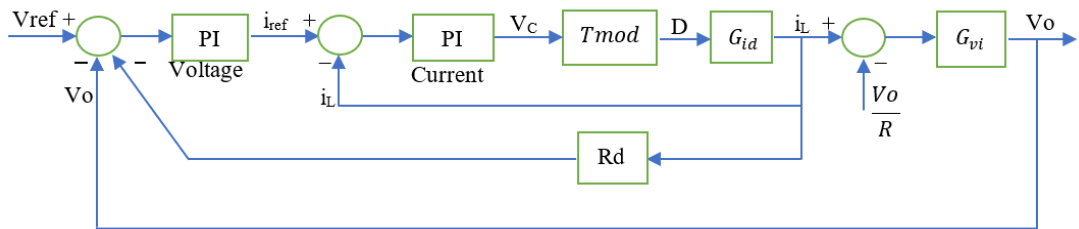


Figure 4.5: Primary Control

The secondary control is responsible and must take rapid action to regulate DC bus voltage if there is any disturbance in the DC Microgrid such as a sudden change in load.

Therefore, the proposed control is based on the average proportional current average voltage controller with an additional technique of circulating current minimization. The overall secondary control concept is depicted in Figure 4.6 while the detailed internal view of average voltage and average proportional current sharing is shown in Figure 4.7(a, b).

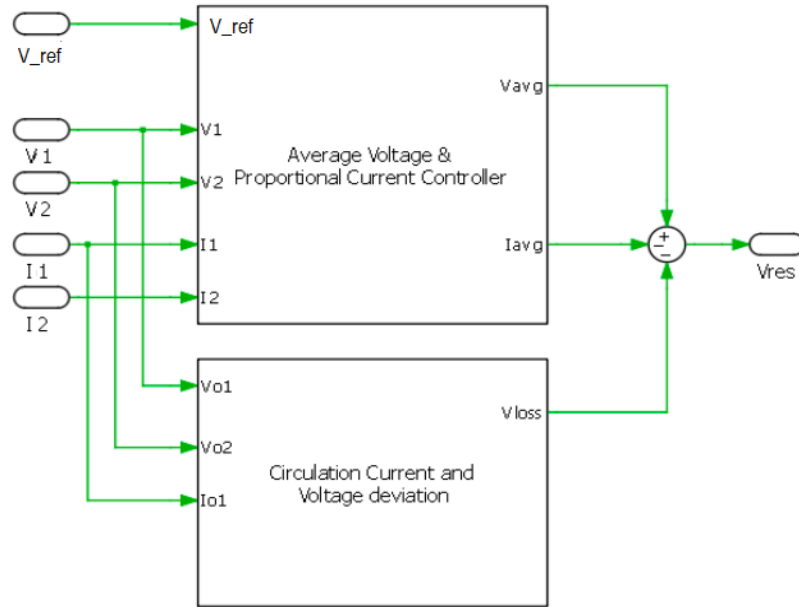


Figure 4.6: Proposed Distributed Secondary Control Strategy

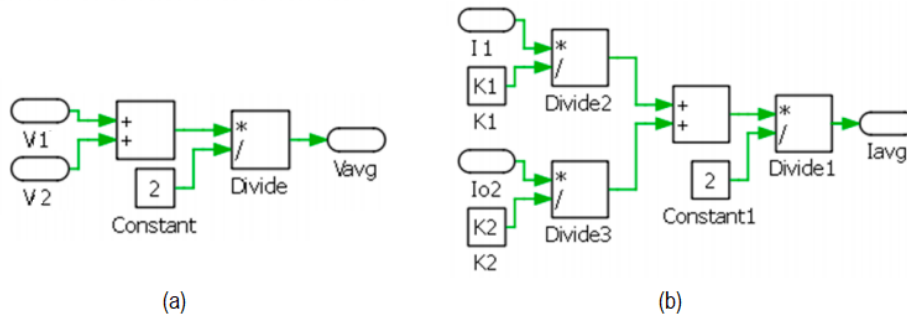


Figure 4.7: (a) Average Voltage Control (b) Average Proportion Current Control

To improve the power sharing accuracy without degrading the system voltage, a circulation currents minimization method is utilized employing Equation 4.5. In this technique, the portion of circulating current is combined with the error signal of classical

average voltage/current method, without any modification in droop coefficients or system parameters. Figure 4.8 represent the circulating current minimization technique.

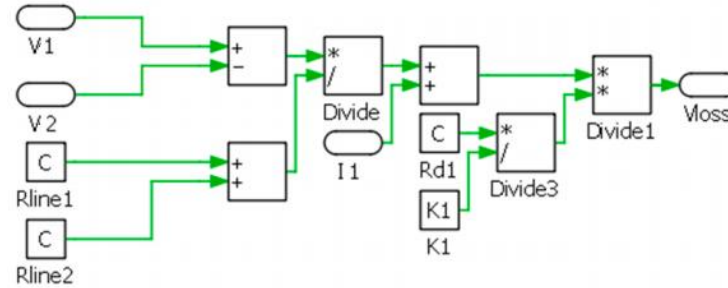


Figure 4.8: Circulating Current Minimization Technique

The reference voltage, “ V_{ref} ” in Figure 4.6 is updated in three levels on the basis of load current to minimize the distribution voltage drop and power loss. This scheme operates based on a tap changer manner of the reference voltage to restore the desired microgrid voltage level as illustrated in Figure 4.9.

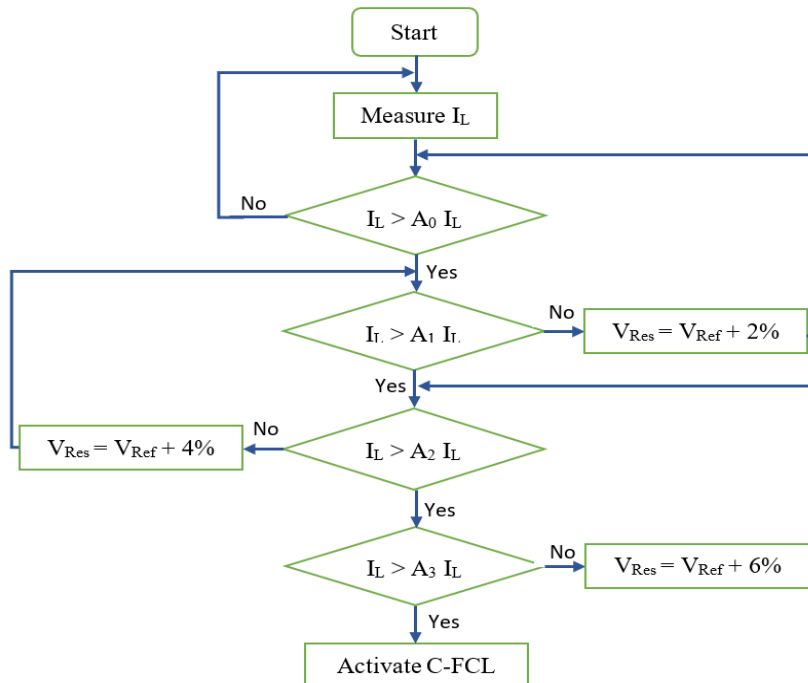


Figure 4.9: Algorithm for Voltage Regulation based on Tap Changing Principle

With the proposed approach, the power converters can be operated in parallel to share a common load and prevent circulating currents. As seen in Figure 4.5, the voltage reference provided to the voltage and current control loops is adjusted by inserting an additional loop with a virtual droop resistance R_d . The output voltage V_0 is calculated as in Equation 4.17, while the value of R_d using Equation 4.18, where ε_v is the maximum permissible voltage deviation; $i_{0,max}$ denotes the maximum output current.

$$V_0 = V_{ref} - (R_d \times i_L) \quad \text{Equation 4.17}$$

$$R_d = \frac{\varepsilon_v}{i_{0,max}} \quad \text{Equation 4.18}$$

To accomplish the goal of the proposed control strategy, Equation 4.17 was modified to include the voltage restoration “ V_{res} ” as given in Equation 4.19.

$$V_0 = V_{ref} - V_{res} - (R_d \times i_L) \quad \text{Equation 4.19}$$

With the application of Equation 4.19, the secondary controller processes the difference between DC bus voltage “ V_{bus} ” and microgrid reference voltage to generate the required voltage restoration that is fed to the control systems of all the converters to rectify bus voltage “ V_{bus} ” and restore the microgrid voltage to the desired level. The modified transfer function for PI controller $P_{res}(s)$ that includes voltage restoration is expressed as in Equation 4.20.

$$P_{res}(s) = \frac{C_v(s) P_v(s)}{1 + C_v(s) P_v(s) \left(1 + \frac{R_d}{G_{vi}(s)}\right)} \quad \text{Equation 4.20}$$

The output voltage level obtained using Equation 4.19 can be adjusted utilizing the developed algorithm in Figure 4.6. In this algorithm, the number of voltage levels and values of coefficients representing the exceeding load current “ A_0, A_1, A_2 and A_3 ” can be selected according to the system operation requirements. This algorithm continuously senses the load

current and modifies the reference voltage accordingly, without affecting the overall system's control.

4.5 Experimental Validation

The theoretical framework of the developed control strategy presented in Section 4.4.2 was validated experimentally using a scaled-down prototype of the DC microgrid system in the lab. The overall grid topology presented in Section 4.5.2 was followed to design the prototype system, however, lower voltage and current levels (one-twentieth of the simulated system) were used in the prototype microgrid system because of power limitations of components and safety considerations.

4.5.1 Automatic Code Generation and Hardware Interfacing

Generally, a control strategy developed in computer software requires interfacing facilities to be implemented on a physical system or plant to behave in a desired manner. MathWorks® provides Embedded Coder (including MATLAB Coder and Simulink Coder) and a variety of hardware support packages to translate the MATLAB functions and Simulink models into machine code (C-code) and run the generated code on different hardware platforms/embedded processor boards (such as Arduino, Raspberry Pi, Intel®, NXP™, STMicroelectronics®, ARM Cortex, and Texas Instruments™) for real-time and nonreal-time applications.

The Embedded Coder enhances the code generated by the Simulink Coder with advanced optimization for precise control that can be easily compiled and executed by any hardware platform for rapid prototyping [145]. Some of the hardware support packages provided by MathWorks® are shown in Figure 4.10.

Embedded Coder (130)

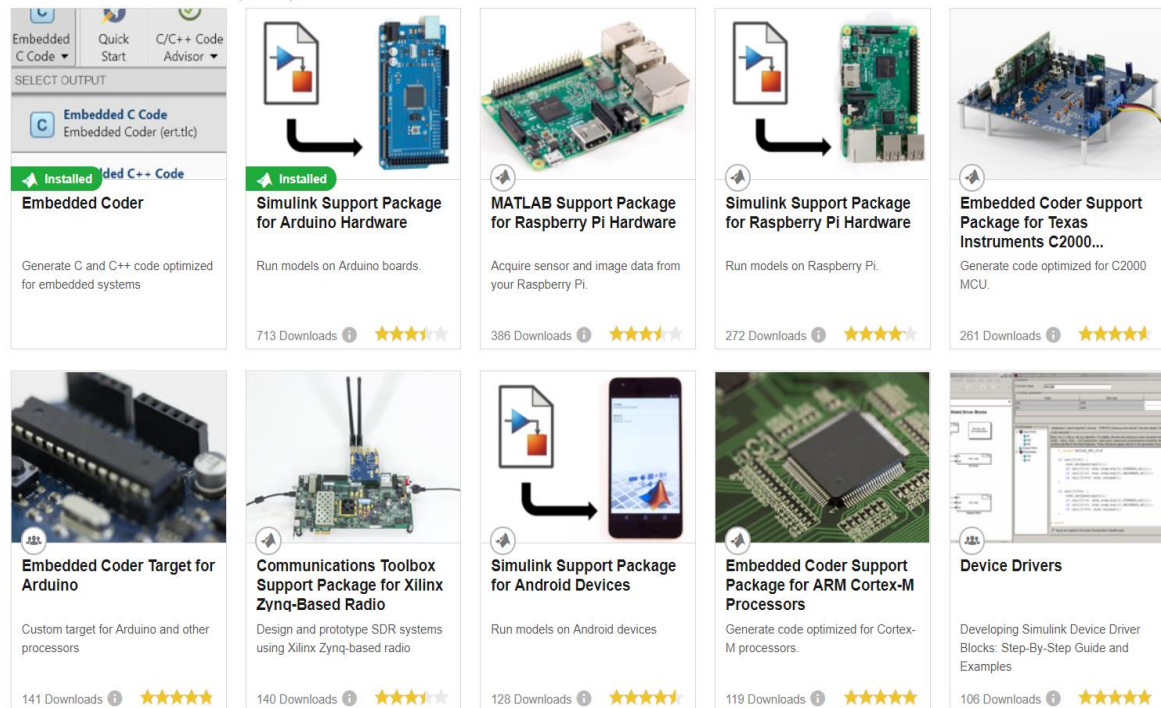


Figure 4.10: Hardware Support Packages Provided by MathWorks

Using Embedded Coder Quick Start for Simulink (from the Code menu tools trip as shown in Figure 4.11), the developed distributed control model was translated into a highly optimized and appropriate C-code that can be efficiently executed by the Arduino platform. Embedded control provides this facility to immerse advanced computing power into the physical world. In addition, Embedded Coder can perform software-in-the-loop and processor-in-the-loop verification.

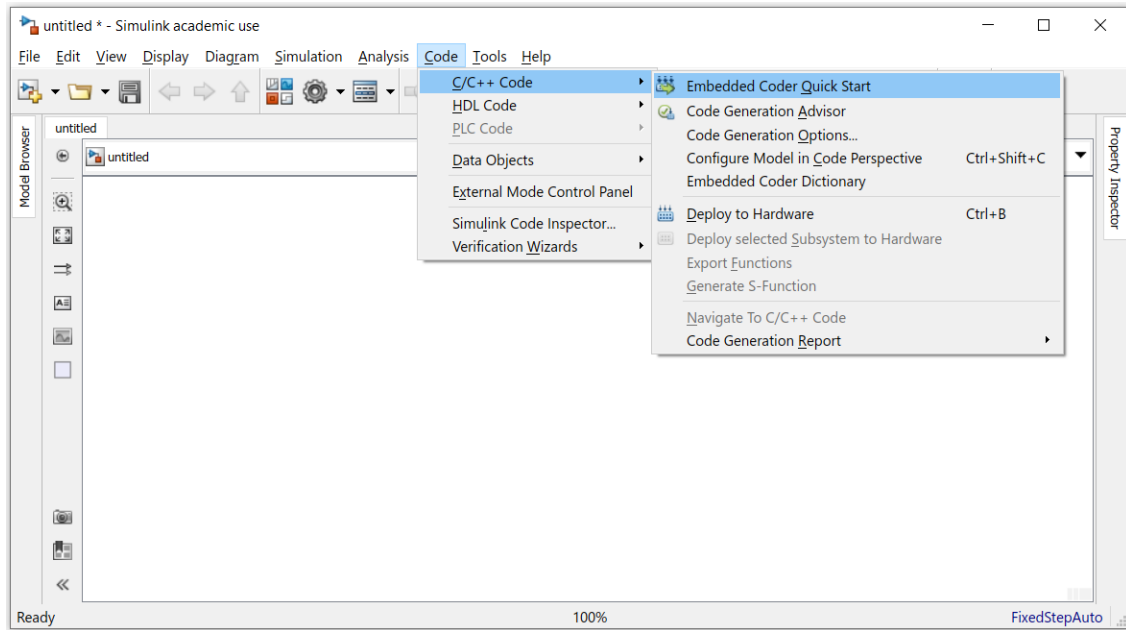


Figure 4.11: Embedded Coder for C-code Generation

Here, it is worth noticing that the appropriate Simulink solver and target hardware used for prototyping should be selected before code generation. The C-code generation procedure is shown in Figure 4.12.

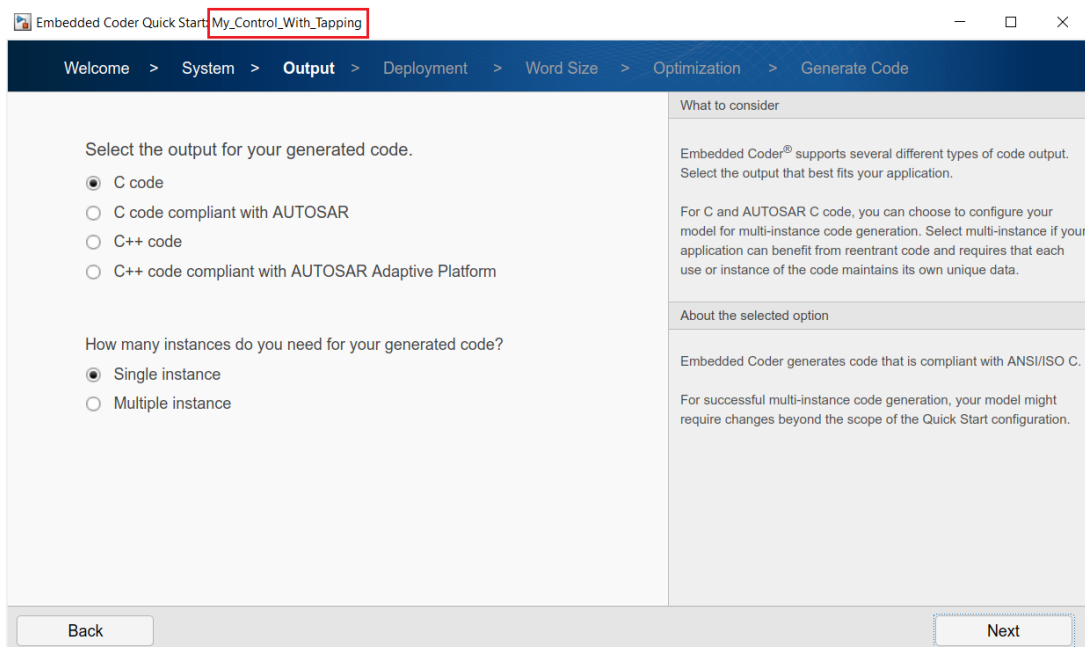


Figure 4.12: Code Generation Procedure using Embedded Coder

4.5.2 Simulink Support Package for Arduino Boards

MathWorks® provides a hardware support package for Arduino boards to deploy the dynamic systems models and/or algorithms, developed in Simulink block diagram environment, onto an Arduino platform for standalone execution. In the support package, a library of Simulink blocks is provided to access and configure inputs and outputs, sensors, actuators, as well as other communication peripherals available on the Arduino hardware. Figure 4.13 shows the main Simulink block library for the Arduino hardware support package.

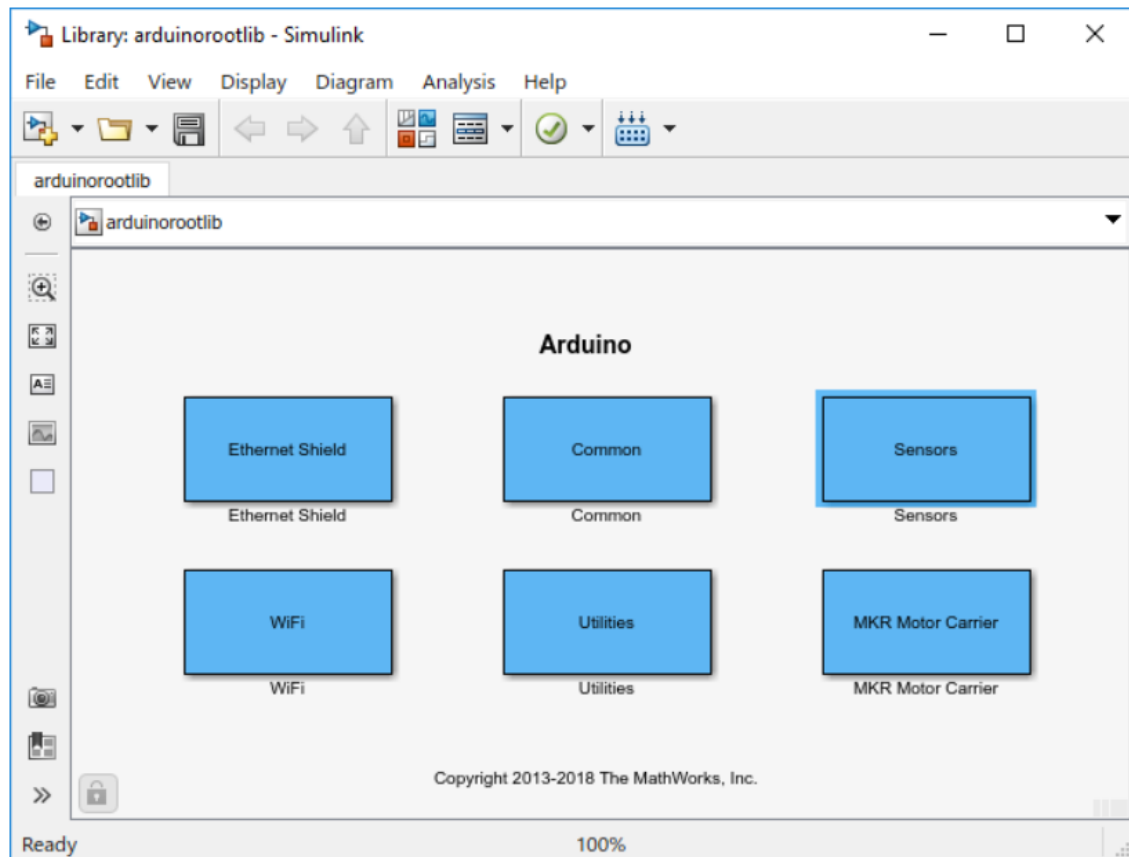


Figure 4.13: Simulink Block Library for Arduino Hardware Support

The sub-libraries (Ethernet Shield, Common, Sensors, and so on) shown in Figure 4.13 consist of Simulink blocks for different functions, configurations, and communications. For instance, the sub-library “Common” contains Simulink blocks for analog/digital I/O,

PWM, serial transmit/receive, I2C read/write, etc. With the help of these Simulink blocks, the Arduino hardware platform can be configured and accessed for data acquisition and control. The Arduino platform incorporates an ATmega328 microcontroller, 14 digital input/output pins, 6 analog inputs, a 16 MHz ceramic resonator, and can communicate with a personal computer through a standard universal serial bus (USB) to transmit and/or receive data. Additionally, the algorithms running on the Arduino board can be monitored and tuned from the same Simulink model [145].

4.5.3 Hardware Target Configuration and Code Deployment

To communicate and deploy the C-code generated from a Simulink model on target hardware, the hardware platform was properly configured. This was done using the model configuration parameters option from the simulation menu of the Simulink model window after connecting the USB cable of Arduino hardware to the host computer as shown in Figure 4.14. From the “Hardware Implementation” tab, the desired hardware board was selected. Additionally, enabled the “Build, load and run” option by clicking on the “Build options” in the hardware board setting.

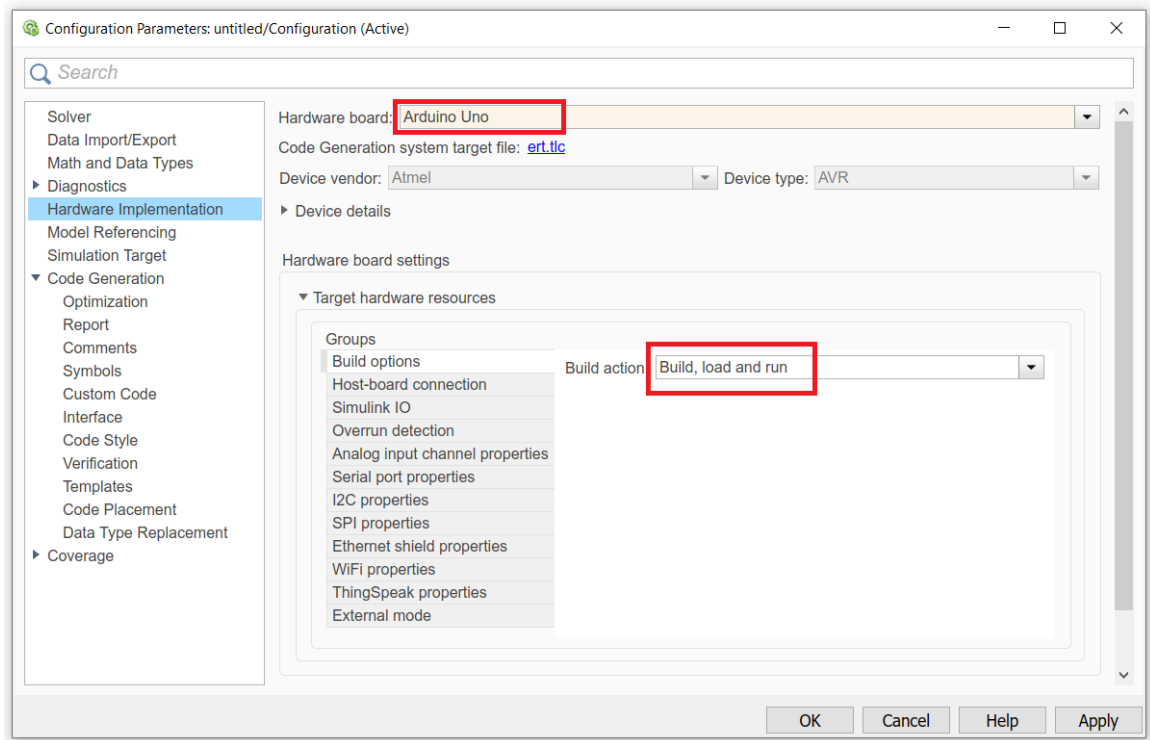


Figure 4.14: Hardware Target Selection and Parameters Configuration

Furthermore, the serial port properties were adjusted in accordance with the Simulink block for serial communication provided in the hardware support package for efficient data communication. Improper data rate will cause serious loss of information between Simulink and target hardware. The Baud rate setting was adjusted to 9600 as shown in Figure 4.15.

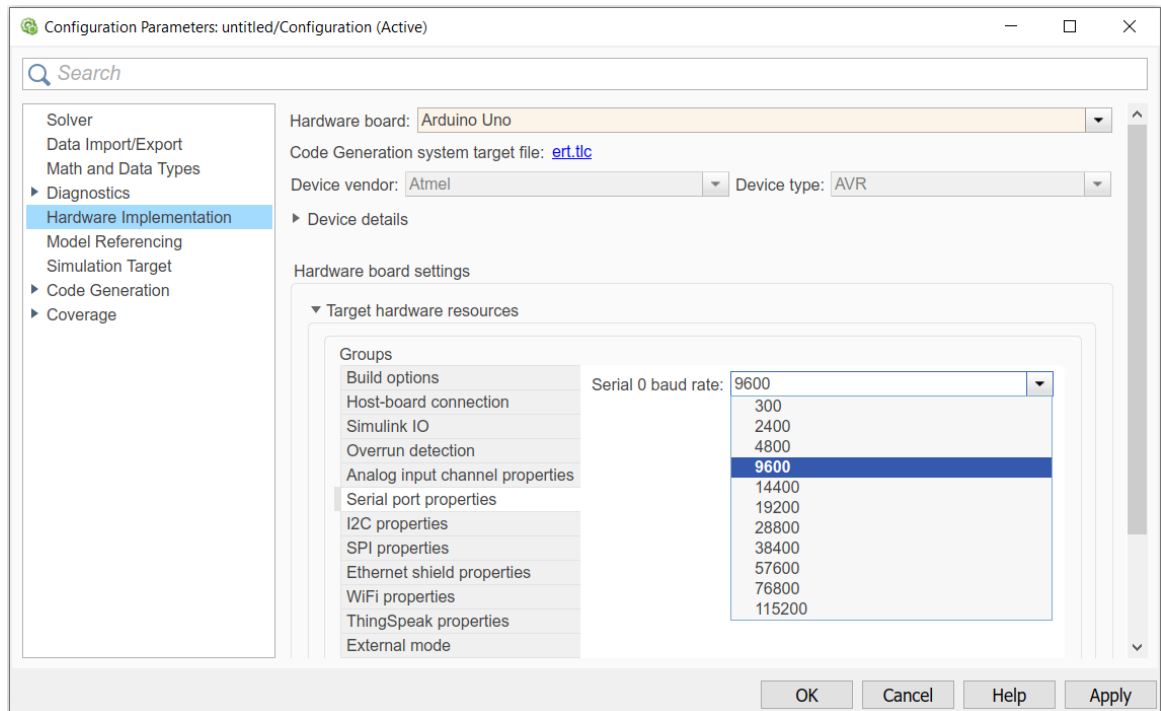


Figure 4.15: Data Rate Setting for Serial Communication

After generating the C-code and hardware interfacing, the code was finally deployed to the hardware as shown in Figure 4.16.

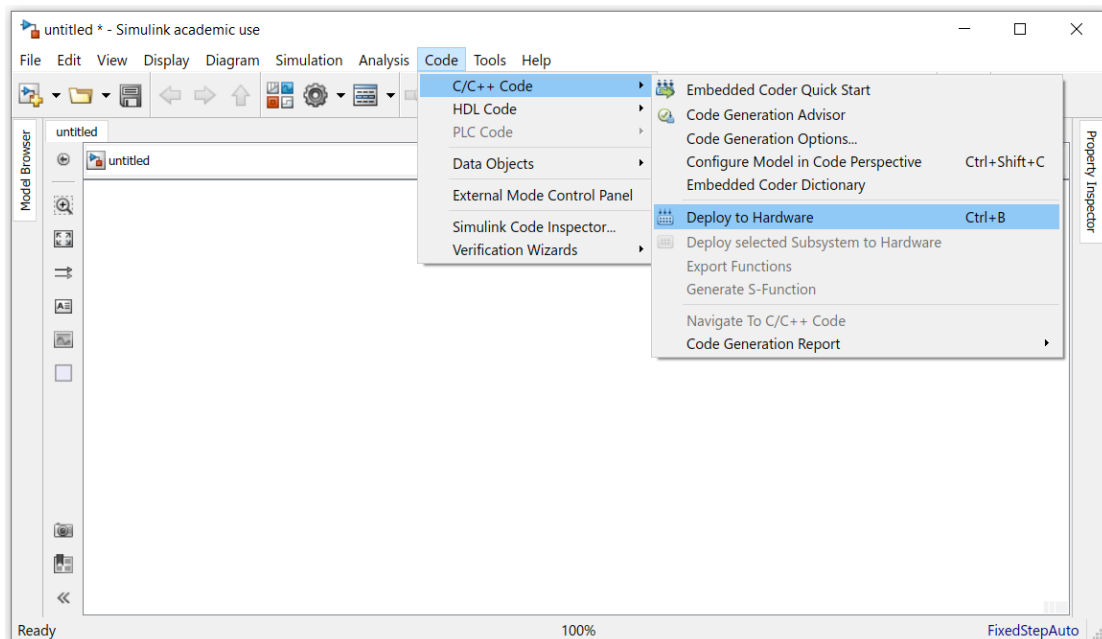


Figure 4.16: Code Deployment to Hardware

4.5.4 Hardware Circuit Configuration

The circuit configuration shown in Figure 4.17 was designed with appropriate values of components to validate the developed control on a scaled-down prototype. It can be seen from the figure that two buck converters are supplying a common load in a parallel fashion. The currents and voltages of both converters, the common DC bus voltage, and the total load current are sensed by Arduino, and the PWM signals of both converters are continuously adjusted using the provided C-code to ensure proper load sharing and voltage regulation. To drive the gate input of high power MOSFETs, gate driver TLP250 was used as a buffer between the low-power Arduino and high-power MOSFETs. Some additional power diodes were used for safe operation. The experimental PCB circuit is shown in Figure 4.18.

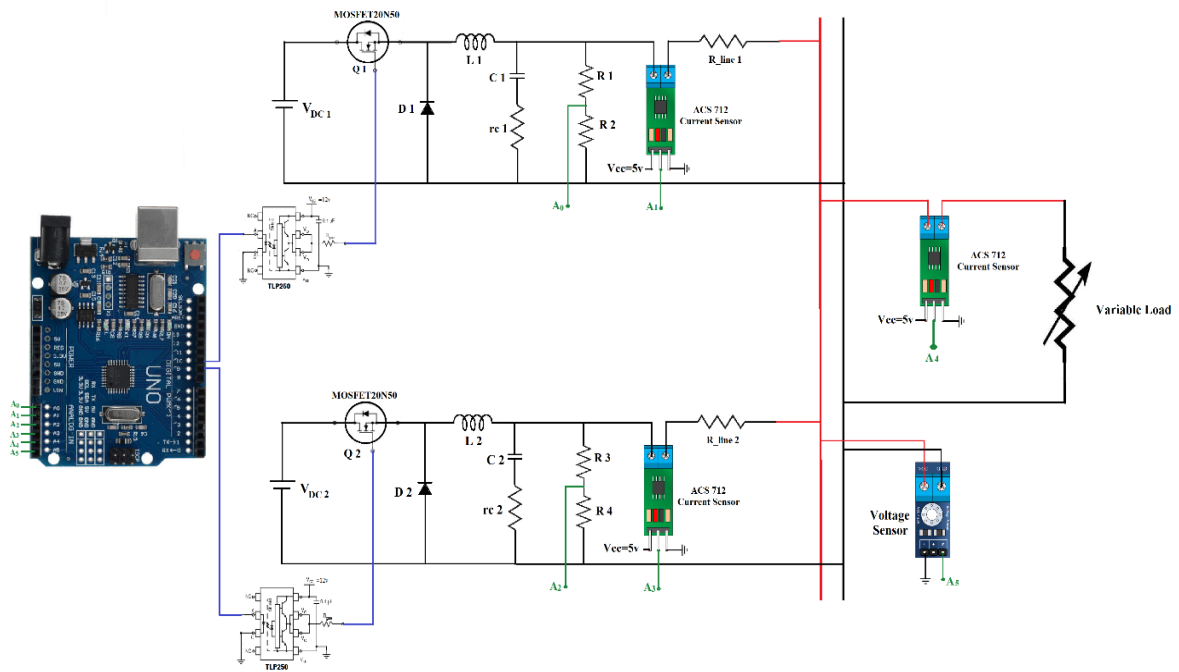


Figure 4.17: Hardware Circuit Configuration

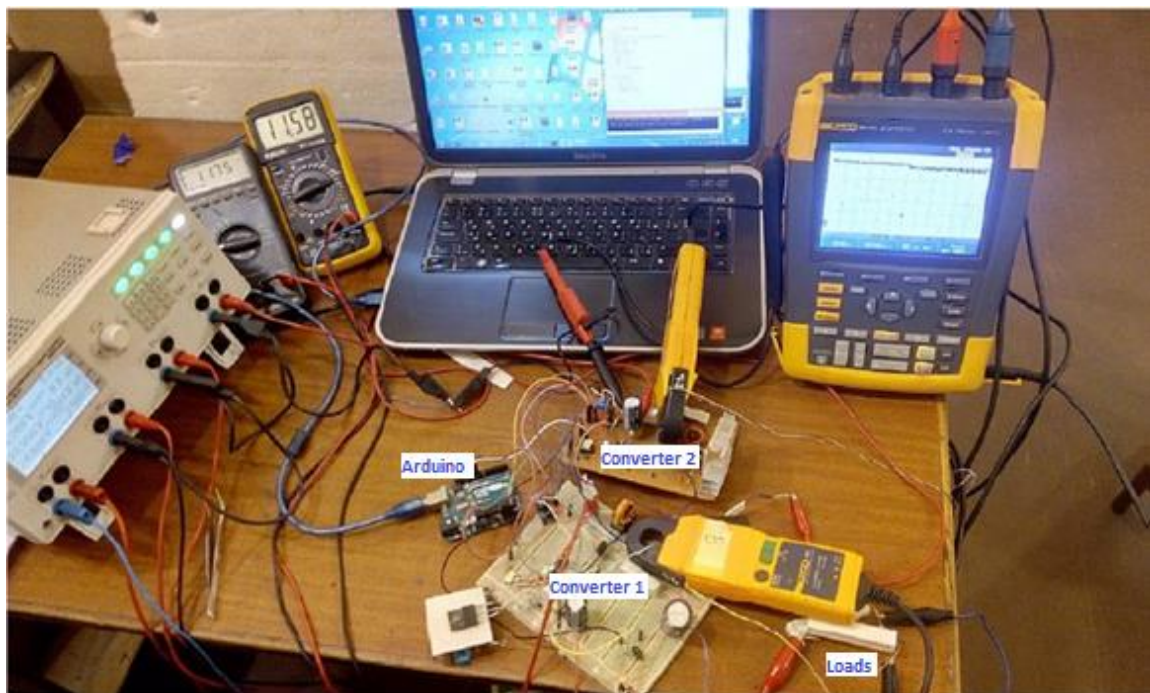


Figure 4.18: Experimental Setup

4.6 Results and Discussions

In this section, the simulation and experimental results obtained by implementing the developed control strategies for voltage regulation and power sharing control are documented in detail. The structure of the test system presented in Figure 4.1 was modeled using MATLAB/Simulink as shown in Figure 4.19.

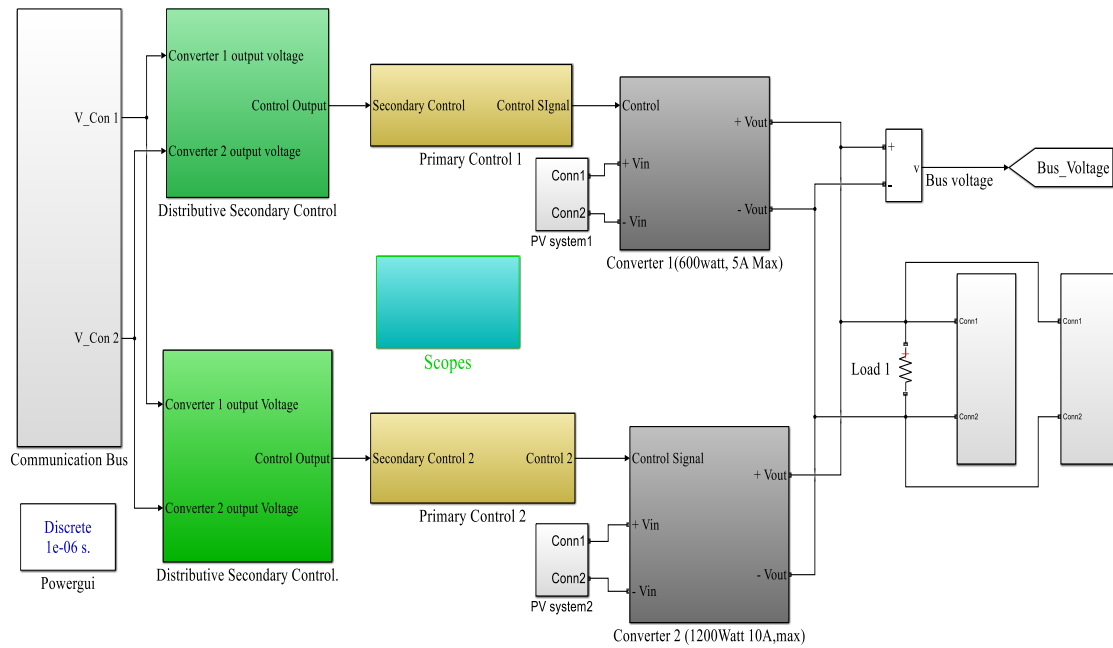


Figure 4.19: Simulink Model of DC Microgrid

The values of inductors, capacitors and the maximum power capacities of both converters are illustrated in Table 4.1.

Table 4.1: Parameters of Paralleled Converters

System Components	Converter 1	Converter 2
Inductance (mH)	41.05	2.053
Capacitance (mF)	26.04	52.08
Max Current (Amp)	5	10
Power Capacity (W)	600	1200

The virtual droop resistances were selected so that the maximum power sharing accuracy with a stable DC bus voltage was achieved. To precisely verify the performance of the proposed technique, the test system was operated under different load conditions in order to analyze the effect of load switching on DC bus voltage and power sharing. Two types of load switching were assumed: a light load switching to represent a change in the load connected to the microgrid and a heavy load switching to represent the tripping of a power source in the neighboring microgrid that imposes a sudden burden on the test system.

In the first case, the proposed technique was compared with the traditional droop control method without introducing the voltage-tapping algorithm, given in Figure 4.9. In the second case, the additional voltage control based on the concept of the tap changing principle was incorporated to reduce the distribution losses during high load conditions.

4.6.1 System Response with Traditional Droop Control Method

Initially, a traditional distributed secondary control with an average voltage/current method was implemented to analyze the power sharing and voltage behavior of the test system. Considering the bus voltage stability as a first priority and making a little compromise on efficient power sharing, the droop coefficients were adjusted so that the voltage deviations due to droop resistances have no significant effect on bus voltage. It can be seen from Figure 4.20 (a) that the power is not accurately shared between converters according to the rated power capacity of each converter.

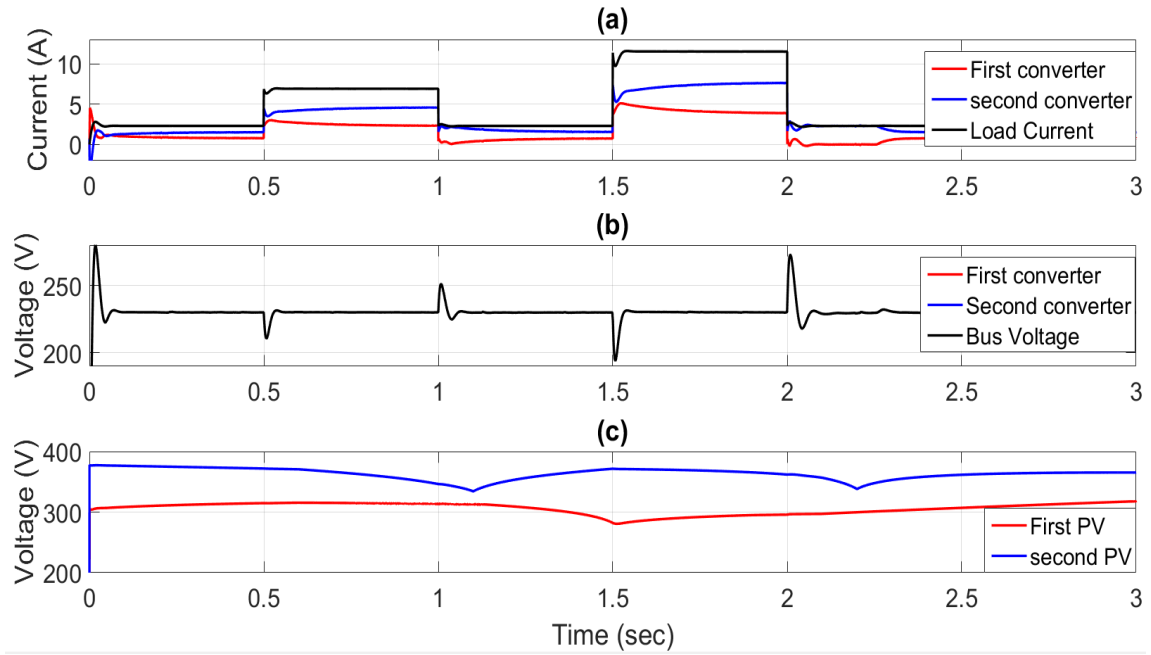


Figure 4.20: System Response using the Average Voltage/Current Control Method

Though the voltages of solar PV arrays varied due to the change in irradiance and temperature as seen in Figure 4.20 (c), the output voltages of converters and DC bus were regulated at the desired output voltage of 230V without any significant deviation imposed by the droop resistances (see Figure 4.20 (b)). The effect of load switching on voltage deviations due to light load switching is within the acceptable range. However, heavy load switching has a significant impact on voltage and can degrade power sharing accuracy.

4.6.2 System Response with the Proposed Control Strategy

After analyzing the response of traditional droop control, the proposed distributed control strategy was implemented on the Simulink model. The results obtained for the proposed control strategy are shown in Figure 4.21.

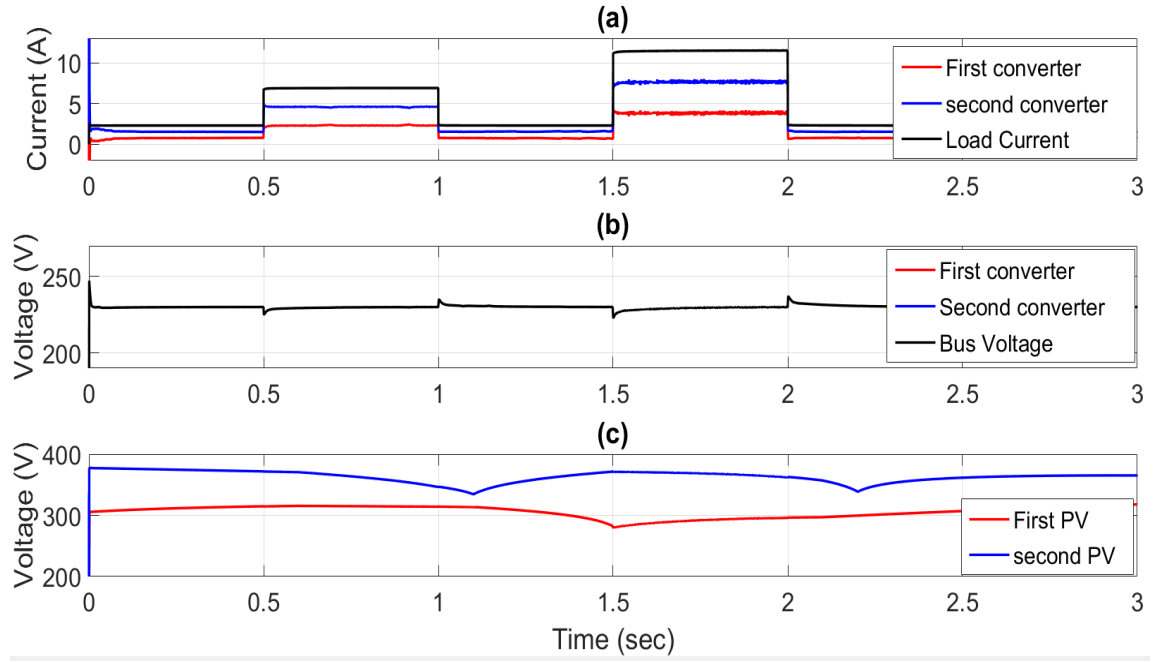


Figure 4.21: System Response using the Proposed Control Strategy

Figure. 4.21 showed that the proposed control technique provides better voltage regulation with a higher power sharing accuracy. The load power is smoothly shared between the power converters as seen in Figure 4.21 (a) without voltage degradation during all operating conditions such as changes in the load and irradiance (see Figure 4.20 (b and c)).

4.6.3 Comparison of the Voltage Deviations due to Load Switching

The voltage deviations due to load switching for traditional droop control and proposed control were compared to verify the performance of the proposed technique as shown in Figure 4.22.

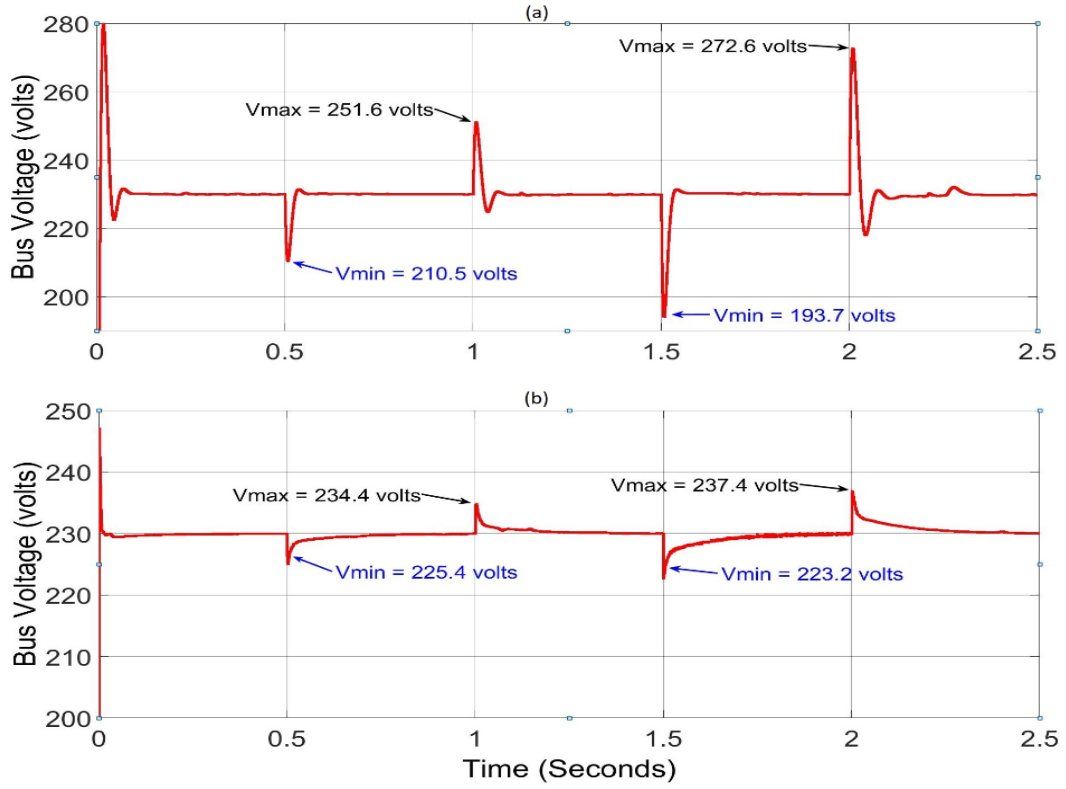


Figure 4.22: Comparison of the Voltage Deviations due to Load Switching

The results in Figure 4.22 (a), it was seen that the DC bus voltage dropped down to a minimum value of 210.5V when the light load was switched on and raised above 250V when the load was switched off. Similarly, due to high load switching, the DC bus voltage drop was significant ($V_{min} = 194V$), also, the voltage rise went beyond the acceptable limits ($V_{max} = 272V$) when the heavy load was switched off. These deviations in voltage may cause a critical risk to the overall system stability. The main reason behind this is the absence of rotating inertia in RES-based power generation. Figure 4.20 (b) clearly shows that the voltage deviations due to load switching were almost negligible when the proposed control technique was implemented.

It is also worth noting that the response of the system to load switching is much faster and the voltage deviations due to load switching are minimized by limiting the currents of converters.

4.6.4 System Response with Multi-tap Reference for Voltage Regulation

Finally, the voltage control with multi-tap reference was introduced to modify the reference voltage in accordance with the load current to minimize the distribution losses. The response of the system control to the load variations can be seen in Figure 4.23.

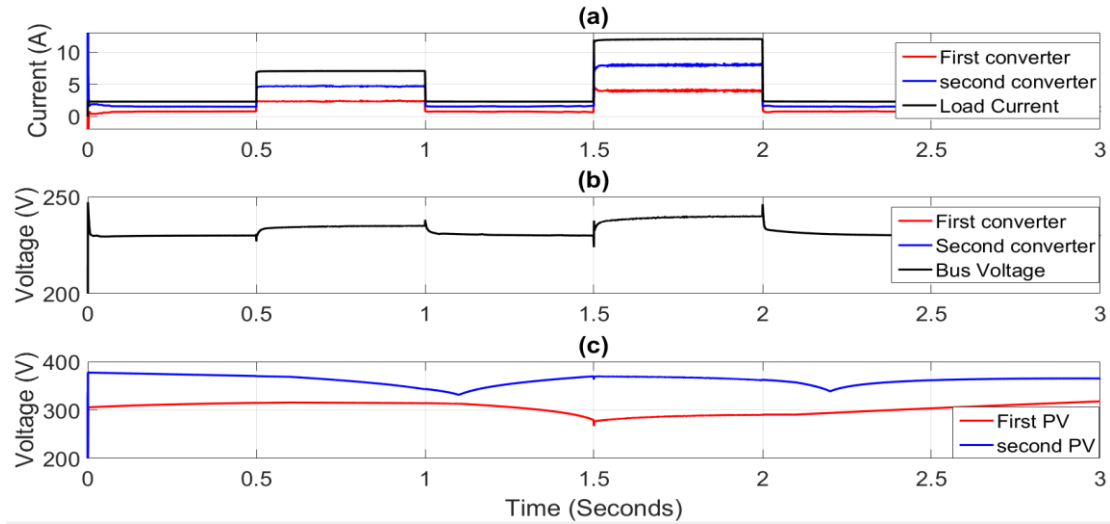


Figure 4.23: System Response using Multi-tap Reference for Voltage Control

As can be observed from this figure, the reference voltage of the microgrid stepped up slightly (2%) when the light load switched on as shown in Figure 4.23 (b). On the other hand, the voltage stepped down when the load switched off. In the same manner, a level of change (4%) in the reference voltage can be observed during heavy load switching. Indeed, the voltage regulation based on tap change control is vital during the overload conditions as it can further improve the voltage stability. It is to be noted that the tap change voltage control has no adverse effect on power sharing or DC bus voltage.

4.6.5 Experimental Results

As discussed in Section 4.5.4, the voltages and currents of both DC-DC converters, total load current and DC bus voltage were sensed by the Arduino to regulate to PWM of both converters simultaneously according to C-code deployed. The data obtained from

Arduino memory was drawn using Matlab/Simulink. The experimental results obtained when the proposed power sharing and voltage regulation control along with the added voltage-tapping function are shown in Figure 4.24.

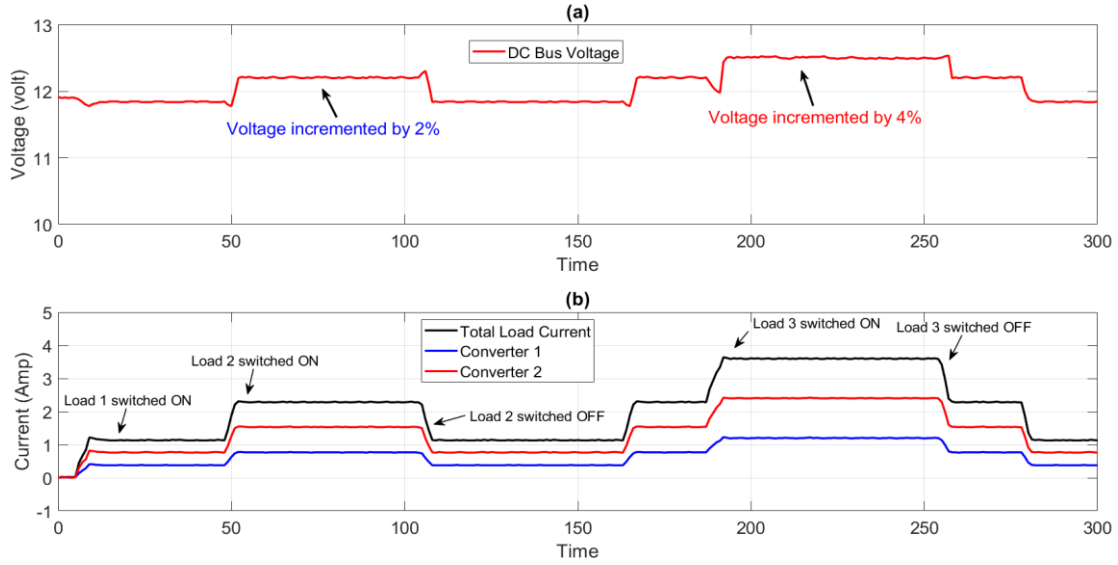


Figure 4.24: Experimental Results

From Figure 4.24 (a), it was verified that the DC bus voltage is increased by 2% when a light load (to represent a change in the load connected to the microgrid) is switched on and vice versa. Similarly, a 4% increase in the microgrid reference voltage was seen when a heavy load (to represent the tripping of a power source in the neighboring microgrid that imposes a sudden burden on the microgrid system) was switched on and vice versa. Figure 4.24 (b) represents that efficient power sharing was achieved in all operating conditions; however, the practical limitations of the components and communication delay have imposed slight variations in the DC bus voltage.

4.7 Performance Comparison

Though the prior studies endeavored to address the technical issues of power-sharing control in DC microgrids, the application of flexible methods for more accurate coordinated

voltage control with the power-sharing strategy remains scattered. The study presented in this thesis discovered the low performance of the previous methods in terms of managing the post-fault minimum/maximum voltage and maintaining its level during load switching. The term stability used in this study is to characterize the behavior of the DC microgrid during the disturbances and after the occurrence of disturbances. Generally, the system can be considered stable during the voltage dips in the microgrid whose voltage profile at any bus is on or above the minimum level (0.85 pu, “-15%”). If the voltage drops below this value, the system is considered unstable. To highlight the novelty of the proposed approach, the performance comparison is detailed in this section.

Weak power-sharing leads to unbalanced situations between generation and demand and thus poor voltage regulation in the DC microgrids. Therefore, the primary focus of the proposed scheme for power sharing and voltage control approach lies in achieving optimal management and coordination amidst various stability challenges, including load fluctuations. The developed distributed control strategies of the DC microgrid as presented in this research work achieve superior results that other innovative methods proposed in [138], [159], [160] cannot attain. Although some combined algorithms including intelligent methods [159], [160] can improve power sharing in DC microgrids surpassing the traditional approach, it is essential to note that the previous methods have limitations in capturing all aspects of microgrid performance particularly, maintaining the stability of power sharing control during fault conditions. Referring to the presented results in this chapter, the recommended control approach effectively regulates the DC voltage, keeping it within a suitable range around the rated DC voltage. Notably, the results of the recent related research studies listed in Table 4.2 do not show the best rapid response performance, exhibiting maximum overshoot and undershooting of voltage and power with a long transient duration

compared to the proposed technique. The fast response in maintaining a stable and well-regulated DC voltage as seen in the results of the above scenarios of the current work, ensures reliable operation and minimum voltage deviations from the desired setpoint when implementing the proposed scheme of power sharing and voltage regulation.

The studies in [138], [159], [160] do not deal with fault management towards mitigating its impact while implementing power-sharing control in DC microgrids. Therefore, the approaches in [138], [159] do not ensure ideal power sharing between microgrid buses and compensate for the fluctuations during disturbances due to the slow response of control algorithms (see Table 4.2). Furthermore, the control methods show slow performance against changes in different scenarios and thus inability to handle the load sharing between parallel-connected converters. On the same note, the power coordinate management approach presented in [160] does not guarantee the best regulation of the DC microgrid as the proposed method presented in the current work.

In the second evaluation of the proposed approach presented in this chapter, the focus shifts to the control of voltage deviations caused by load switching of DC microgrid buses. The objective is to enhance the control of DC voltage, and power-sharing to ensure better regulation and efficient energy transfer. The analysis and contrastive evaluation of the obtained results as depicted in Figures 4.20 – 4.24 highlight the excellence of the proposed technique, as the outcomes demonstrate the fastest transient response. It can be concluded that the assessment of the voltage control with multi-tap reference during load disturbances emphasizes the effectiveness of the proposed method, compared to alternative techniques listed in Table 4. 2. This indicates that the proposed algorithm in the current work is pivotal for both power-sharing and voltage regulation.

Table 4.2: Performance comparison summary

Recent related research work	Control approach	Limitations of the approach	DC bus voltage deviation ($\pm\%$)	Duration of stable power-sharing operation (Sec)
Current work	An improved distributed control strategy is developed with fault current mitigation for power sharing and voltage regulation. An additional current feedback loop was introduced to modify the microgrid reference voltage during overload conditions.	Mitigation technique during fault conditions. This limitation has been addressed in the next chapter by developing a robust fault current preventive scheme based on a controllable fault current limiter.	+1.7 – 2	0.25
[159]	The hierarchical droop control scheme was proposed for power sharing, and the fuzzy iterative method was added to reduce the voltage deviation induced by droop control.	The overall approach involves many control schemes and does not ensure the most efficient choice of coefficients, which may lead to delays while operating the system during unsteady conditions.	+4	12

Table 4.2 continued

[160]	A droop-based sliding mode controller was designed for power-sharing in an isolated DC microgrid. A fuzzy approximator was added to compensate for the uncertainties in the nonlinear droop model.	The method is complicated and needs to be carefully designed. Further, it is not suitable for large-capacity microgrids. The combination of techniques produces unknown parameters, which leads to an increase in complexity, and thus, a challenging paradigm.	+1 −0.95	1.5
[138]	A dynamic solving algorithm based on the primal-dual decomposition method was proposed using unified distributed optimal control. The algorithm can provide commands for power and voltage control including droop control in both transient process and steady state.	The tie-line limit is not considered in this study, which is very important when a large disturbance happens. Therefore, this approach does not ensure ideal power sharing and best voltage regulation during disturbances. Moreover, the process to optimize the operation of the system lengthens transit time during steady states.	−5.8	5

4.8 Chapter Summary

This chapter has presented a distributed secondary control strategy for voltage regulation and power sharing in DC microgrids. The performance of the proposed control was verified by comparing the obtained results with the traditional droop control method as well as experimental results. It was revealed that the proposed control strategy has better voltage regulation performance with higher power sharing accuracy and fast system

response. Furthermore, the voltage deviations due to load switching were significantly reduced owing to the tap change control of the reference voltage. This can help in reducing the power distribution losses during overload conditions, as a result, increasing DC microgrid reliability.

CHAPTER 5

FAULT CURRENT LIMITER

5.1 Introduction

As discussed in Chapter 3 (Section 3.5.2), DC systems are more vulnerable to faults and transient disturbances. The high-magnitude fault currents should be efficiently limited to ensure microgrid stability in terms of voltage regulation and power sharing. In this chapter, a robust fault current preventive scheme based on a controllable fault current limiter (C-FCL) has been presented to limit short-circuit fault currents and to mitigate the impact of fault on voltage regulation and power sharing control in a ring DC microgrid configuration.

The functionality of the proposed C-FCL is achieved using intelligent switching control followed by impedance control. To eliminate the coordination time delay, the C-FCL uses local measurements to detect the fault for providing a quick response to initiate the switching DC short-circuit fault current. The modeling and calculation for optimal resistance values of the fault current limiter are also presented.

5.2 Requirement of Smart FCL

In overhead lines, more than 80% of short-circuit faults are temporary having a time duration in milliseconds. Such transient faults may not be properly detected and cleared by the protection system which may result in shifting the IGBTs into a self-blocking state. In this case, the coordinated control between power converters could be lost thus, leading the system into instability status. Fault current limiters (FCLs) have been applied in power generation, transmission, and distribution networks in order to prevent damage from faults, protection improvement, stability enhancement, fault ride through capability enhancement,

and to avoid the inevitable upgradation of different equipment. An ideal current limiter should have zero impedance during normal operations, be able to get instantly involved to limit the fault current with high impedance during fault conditions, and provide a fast recovery after the fault [146], [147].

In an isolated multi-terminal DC (MTDC) network, the magnitude of the fault current depends on fault location, and the use of FCL based on fixed impedance will not enable the protection scheme to limit the fault current to the desired level. Hence, new fault current limiting techniques should be devised to overcome the above-mentioned issues so that the stable system operation and safety of the grid equipment can be ensured.

5.3 Fault Current Modelling in DC Systems

Fault analysis is vital for the design of protective devices and distribution equipment used in the power grid. The short-circuit calculation is widely used for relay protection (settings, coordination, sensitivity, etc.), fuse and breaker capacity check, fault location, supply restoration, etc. [148]. In this study, fault current calculation was carried out to assist in identifying the threshold values of controllable current limiters. The characteristics of DC short-circuit fault current were further analyzed to better understand the behavior of DC microgrid systems during fault conditions and to measure the withstand capabilities of switching equipment and protective devices.

Generally, during the fault conditions, each power source contributes to the total short-circuit current, hence, the superposition principle shall be applied in fault analysis. In the fault scenario of DC systems, the magnitudes of short-circuit currents, values of line parameters, and protective equipment can be ascertained from measurements taken by assuming a specific short-circuit location. It may also be determined from system tests or

measurements on model systems. The standardized and commonly applicable method for calculating short-circuit currents with sufficient accuracy in auxiliary DC systems in substations and power plants is provided by IEC 61660 [149]. According to IEC, while calculating the short-circuit current, load current is not considered. However, it is essential to distinguish between the maximum and minimum values of short-circuit current. The maximum value of short-circuit-current determines the rating of the electrical cables, buses, and other associated equipment while the minimum value is taken as the basis for protection ratings and settings. Figure 5.1 represents the standard short-circuit current curve used for fault analysis in DC systems.

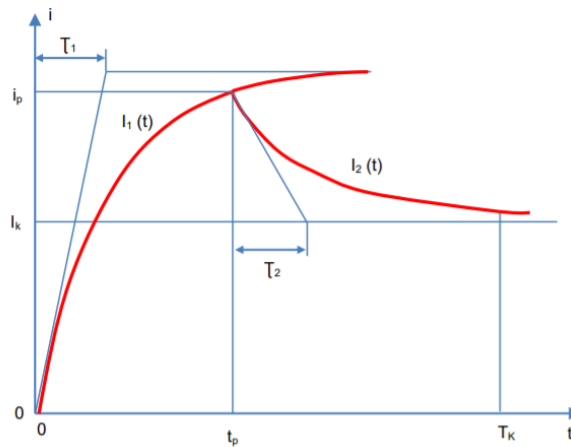


Figure 5.1: Standard Short-circuit Function Curve According to IEC Standard [149]

Referring to Figure 5.1, the individual short-circuit current for each power source is calculated as follows:

$$i_1(t) = i_p \frac{1 - e^{-\frac{t}{\tau_1}}}{1 - e^{-\frac{t_p}{\tau_1}}} \quad \text{Equation 5.1}$$

$$i_2(t) = i_p \left[(1 - \alpha) e^{-(t-t_p)\tau_2} + \alpha \right] \begin{cases} t \geq t_p \\ \alpha = \frac{i_p}{i_k} \end{cases} \quad \text{Equation 5.2}$$

where i_p and I_k are the peak value of short-circuit current and quasi steady-state value of short-circuit current respectively while t_p represents the time duration to reach the peak value and T_k is the short-circuit duration. τ_1 and τ_2 represent the rise time constant and decay time constant, respectively. The total short-circuit current (i_{sc}) for n number of power sources is determined using Equation 5.3 where j represents the observed power source.

$$i_{sc}(t) = \sum_{j=1}^n i_{1j}(t) + i_{2j}(t) \quad [0 \leq t \leq T_k] \quad \text{Equation 5.3}$$

Usually, the quasi steady-state value of fault current is assumed as the magnitude of fault current after 1 second of short-circuit fault occurrence [149]. In the absence of a certain quasi steady-state value, the value of short-circuit is calculated using Equation 5.1 only. Though this method provides more accurate values, it cannot be used in the absence of specific values of i_p , I_k , t_p , τ_1 and τ_2 , which are obtained from system tests or measurements on a model system. In such a situation, the generalized method can be used to determine the magnitude of fault current in DC systems.

When a short-circuit fault occurs in a DC microgrid, the magnitude of the fault current depends on the system voltage and impedance of the fault current path (from source to fault location). According to IEEE Std 946-2004 [101], in LVDC distribution systems, the nominal voltage of 250 volts is utilized to supply power to DC pumping stations and large inverters while 125 volts is used for relay logic circuits and switchgear applications. Further lower DC voltages of 48 volts, 24 volts, and 12 volts are used for specific

applications and instrumentation. According to [150], the fault current $I_f(t)$ contribution of each power source is generally given by Equation 5.4.

$$I_f(t) = \frac{V_s}{R_{eq}} \left(1 - e^{-\frac{R_{eq}}{L_{eq}}t} \right) \quad \text{Equation 5.4}$$

Where V_s denotes the system voltage while R_{eq} and L_{eq} represent the equivalent resistance and equivalent inductance of the current path, respectively. A lower impedance of the fault current path could reverse the polarity of current at the load end and the load will not be supplied at all. Considering Equation 5.4, the time constant of the DC fault current becomes much smaller because of the lower resistance of DC lines compared to the high reactance of AC lines and the DC system voltage will drop drastically or even collapse [150].

If n number of power sources are installed in the micro-grid system, then Equation 5.4 can be modified as:

$$I_{f(total)}(t) = \sum_{j=1}^n \frac{V_s}{R_{eq}^*} \left(1 - e^{-\frac{R_{eq}^*}{L_{eq}^*}t} \right) \quad \text{Equation 5.5}$$

Where R_{eq}^* and L_{eq}^* represent the equivalent resistance and equivalent inductance of the current path from that particular power source (j^{th} source) to the fault location.

5.4 Proposed Fault Current Preventive Scheme

The fault current preventive scheme presented in this study is to mitigate the vulnerability of DC microgrid control against transient short-circuit faults. Referring to previous studies (Chapter 4), an improved distributed control was developed to ensure proper load power sharing and voltage control between multiple DC-DC converters of different power capacities in a DC microgrid. The topology and single-line diagram of the multiple-source DC system with the protection scheme is shown in Figure 5.2 (a, b) where two solar

photovoltaic (PV) systems are sharing the total load connected to the system. It can be seen in this figure that during the daytime, the load at bus 3 is normally supplied by the solar PV systems while at night-time, it is completely disconnected and supplied by energy storage or an auxiliary diesel generator. In either case, the DC microgrid control can perform efficiently to share the total load connected to all three buses without any voltage or power sharing instability. However, when the system was subjected to short-circuit faults, it was observed that the system control failed to recover efficiently. The main objective of this study is to mitigate the vulnerability of a ring DC microgrid configuration during short-circuit faults using a controllable current limiter.

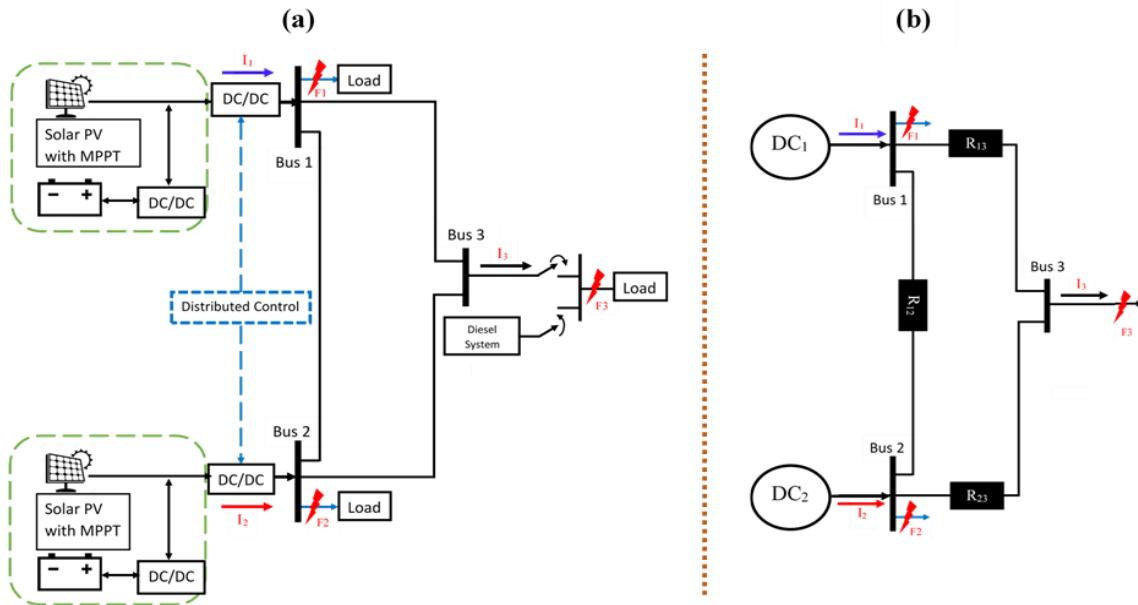


Figure 5.2: Test System; (a) Topology (b) Single-line Diagram

As discussed in Section 5.3, the magnitude of fault current depends on the system voltage and current path impedance. From Equation 5.4, it is clear that low resistance and negligible inductance of DC lines is a severe threat when faults occur, therefore, FCL is normally used as a preventive step. In the case of a stand-alone DC microgrid, to avoid the self-protection stage of IGBTs, the impedance value of FCL can be selected by considering

the maximum allowable current of power converters. Nevertheless, in a ring DC microgrid configuration, a fixed value of the FCL impedance as proposed in the literature cannot provide the same functionality for different fault locations. The main reasons for this are the dissimilar impedances of lines and the change in power contribution from each converter depending on capacity and location. To address these issues, a controllable impedance for DC microgrid protection is proposed to limit fault currents and improve the dynamic stability of the system control. The proposed C-FCL uses power electronics switches to shift the fault current to another branch with controllable resistance (R_{FCL}) to limit current flow from power converters. The general concept of C-FCL functionality is depicted in Figure 5.3.

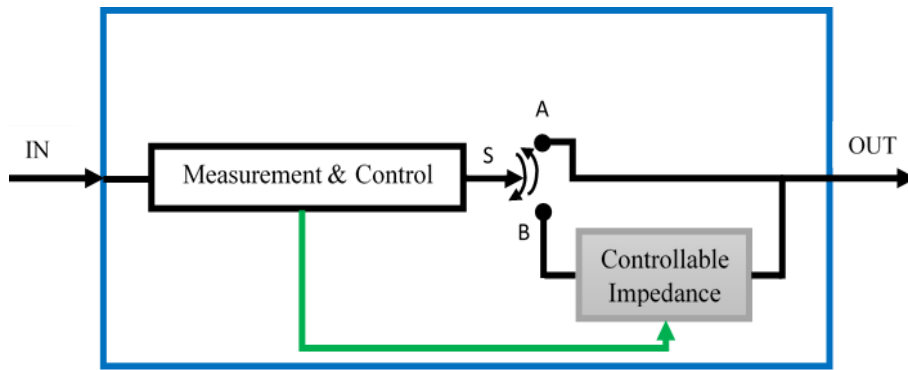


Figure 5.3: Bus Configuration with Proposed C-FCL

The controllable fault current limiter as shown in above figure was designed based on decision rules in such a way that when the protection scheme detects any rise in the maximum allowable value of current " I_i^{max} " in any particular bus " i " at a time " t_f ". In this sense, the current limiter operates by switching a suitable value of the controllable resistor " R_i^F " which is dynamically determined using the real-time voltage " V_i " and current " I_i " values at each bus. Accordingly, the power balance equation of the microgrid at bus " i " can be written as,

$$P_{PV,i}(t) + P_{ES,i}(t) = P_{L,i}(t) + P_{LS,kl}(t) \quad \text{Equation 5.6}$$

where, $P_{PV,i}(t)$, $P_{ES,i}(t)$, and $P_{L,i}(t)$ are solar PV, energy storage, and bus load at time “ t ” respectively; $P_{LS,kl}(t)$ is the power loss of the line between buses “ i ” and “ j ”. Referring to Equations 5.4 and 5.5, when fault “F” occurs, the injection of short-circuit current “ I_i^F ” into the faulty bus will cause changes in the power flow of the whole system. This is due to the fact that different fault locations result in changing the system configuration leading to variations in the voltage and current of each bus. Hence, the expression for selecting the switching value of the current limiter in Equation 5.7 holds true, where R_{ij}^F signifies the resistance of the current path between any particular bus “ i ” and fault location “ j ”.

$$R_i^F = \frac{V_i}{I_i} - R_{ik}^F \begin{cases} I_i^{max} < I_i^F(t_f) = \frac{V_i}{R_{ij}} \left(1 - e^{-\frac{R_{ij}}{L_{ij}}t} \right) \\ F = 1, \dots, j \end{cases} \quad \text{Equation 5.7}$$

5.5 Calculation for C-FCL Resistances for Different Fault Locations

Considering the test system (shown in Figure 5.2(a)), the required values of R_{FCL} for different fault locations (F_1 , F_2 and F_3) were determined by applying Ohm’s law in each case. The single line diagram of the test system is shown in Figure 5.2(b) where DC_1 and DC_2 represent power converter 1 and 2 respectively while R_{12} , R_{13} , and R_{23} represent the line resistances between buses; while the small DC inductances of distribution line were neglected.

To calculate values of R_{FCL} in each bus for fault locations (F_1 , F_2 and F_3), the maximum allowable currents of power converters 1 and 2 were taken as I_{1MAX} and I_{2MAX} respectively that would be contributed by power converters during fault conditions. The

microgrid voltage is represented by V_s . By considering the fault current contribution of converter 1 and converter 2 equal to the maximum allowable current I_{1MAX} and I_{2MAX} respectively, the required values for R_{FCL} for both converters were calculated as:

i. For fault location F_1 :

$$R_{eq_1(F1)} = \frac{V_s}{I_{1MAX}} \quad \text{Equation 5.8}$$

Where $R_{eq_1(F1)}$ is equivalent resistance from converter 1 to fault location F_1 and is given by Equation 5.9.

$$R_{eq_1(F1)} = R_{FCL1(F1)} + R_{CP1(F1)} \quad \text{Equation 5.9}$$

In Equation 5.9, $R_{FCL1(F1)}$ represents the required resistance for FCL in bus 1 for fault location F_1 and $R_{CP1(F1)}$ represents the resistance of current path from converter 1 to the fault location F_1 which is equal to zero as there is no line resistance involved. Similarly:

$$R_{eq_2(F1)} = \frac{V_s}{I_{2MAX}} \quad \text{Equation 5.10}$$

Where $R_{eq_2(F1)}$ is equivalent resistance from converter 2 to fault location F_1 and is given as:

$$R_{eq_2(F1)} = R_{FCL2(F1)} + R_{CP2(F1)} \quad \text{Equation 5.11}$$

In Equation 5.11, $R_{FCL2(F1)}$ represents the required resistance for FCL in bus 2 for fault location F_1 and $R_{CP2(F1)}$ represents the resistance of current path from converter 2 to the fault location F_1 which is equal to the line resistance R_{12} .

ii. For fault location F_2 :

$$R_{eq_1(F2)} = \frac{V_s}{I_{1MAX}} \quad \text{Equation 5.12}$$

Where $R_{eq_1(F2)}$ is equivalent resistance from converter 1 to fault location F_2 .

$$R_{eq_1(F2)} = R_{FCL1(F2)} + R_{CP1(F2)} \quad \text{Equation 5.13}$$

In Equation 5.13, $R_{FCL1(F2)}$ represents the required resistance for FCL in bus 1 for fault location F_2 and $R_{CP1(F2)}$ represents the resistance of current path from converter 1 to the fault location F_2 which is equal to the line resistance R_{12} .

Similarly:

$$R_{eq_2(F2)} = \frac{V_s}{I_{2MAX}} \quad \text{Equation 5.14}$$

Where $R_{eq_2(F2)}$ is equivalent resistance from converter 2 to fault location F_2 and is given as:

$$R_{eq_2(F2)} = R_{FCL2(F2)} + R_{CP2(F2)} \quad \text{Equation 5.15}$$

Here, $R_{FCL2(F2)}$ represents the required resistance for FCL in bus 2 for fault location F_2 and $R_{CP2(F2)}$ represents the resistance of the current path from converter 2 to the fault location F_2 , equal to zero as there is no line resistance.

iii. For fault location F_3 :

$$R_{eq_1(F3)} = \frac{V_s}{I_{1MAX}} \quad \text{Equation 5.16}$$

Where $R_{eq_1(F3)}$ is equivalent resistance from converter 1 to fault location F_3 and is calculated as:

$$R_{eq_1(F3)} = R_{FCL1(F3)} + R_{CP1(F3)} \quad \text{Equation 5.17}$$

In Equation 5.17, $R_{FCL1(F3)}$ represents the required resistance for FCL in bus 1 for fault location F_3 and $R_{CP1(F3)}$ represents the resistance of current path from converter 1 to the fault location F_3 , equal to R_{13} .

Similarly:

$$R_{eq_2(F3)} = \frac{V_s}{I_{2MAX}} \quad \text{Equation 5.18}$$

Where $R_{eq_2(F3)}$ is equivalent resistance from converter 2 to fault location F_3 and is given as:

$$R_{eq_2(F3)} = R_{FCL2(F3)} + R_{CP2(F3)} \quad \text{Equation 5.19}$$

Where $R_{FCL2(F3)}$ represents the required resistance for FCL in bus 2 for fault location F_3 and $R_{CP2(F3)}$ represents the resistance of the current path from converter 2 to the fault location F_1 , which equals to R_{23} .

5.6 Algorithm for Smart FCL

The above calculations indicated that the values of FCL resistances in each bus should be varied according to the fault location. To address this issue, the concept of controllable resistance was proposed. To select the appropriate values of controllable resistance, the developed switching algorithm is shown in Figure 5.4.

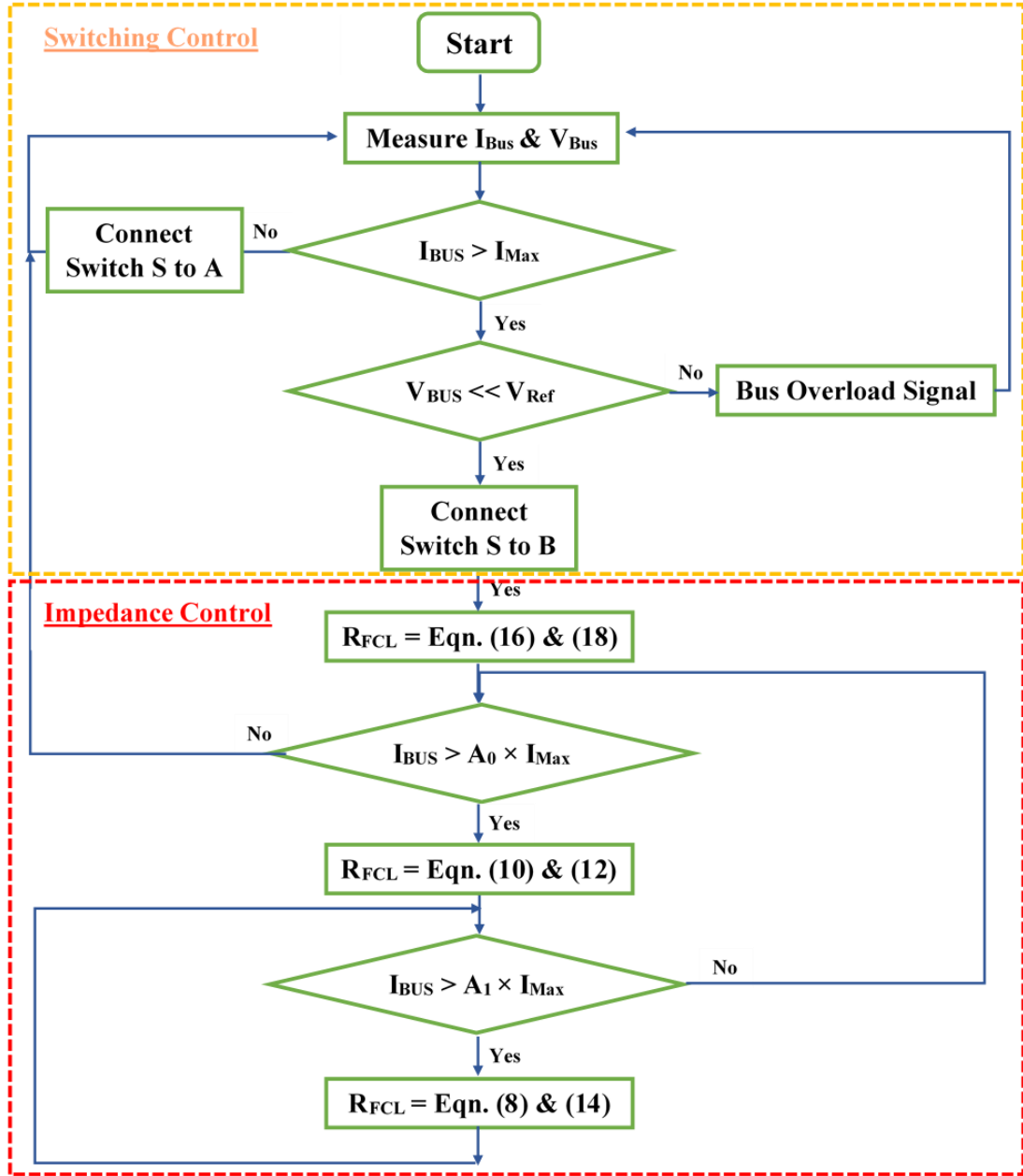


Figure 5.4: Proposed Control Algorithm for C-FCL

In reference to Figure 5.3, the proposed algorithm for C-FCL in Figure 5.4 has two control objectives, i.e., the switch control and impedance control. The switch control objective is achieved by measuring the bus voltage and current while the impedance control objective is achieved by measuring the bus current only. As discussed earlier, due to lower impedances of DC lines, the system voltage drops drastically. and hence, the bus current is taken as the main decisive factor for impedance control. When a fault occurs, the switch “S”

is shifted to point “B” from point “A” (Figure 5.3) and the lowest values of resistances for each C-FCL are selected, assuming the farthest fault location (F_3). The limited bus current is again compared with other pre-defined values ($A_0 I_{MAX}$ and $A_1 I_{MAX}$) for different fault locations and the resistance is varied accordingly. The Simulink model to implement the proposed C-FCL algorithm is shown in Figure 5.5.

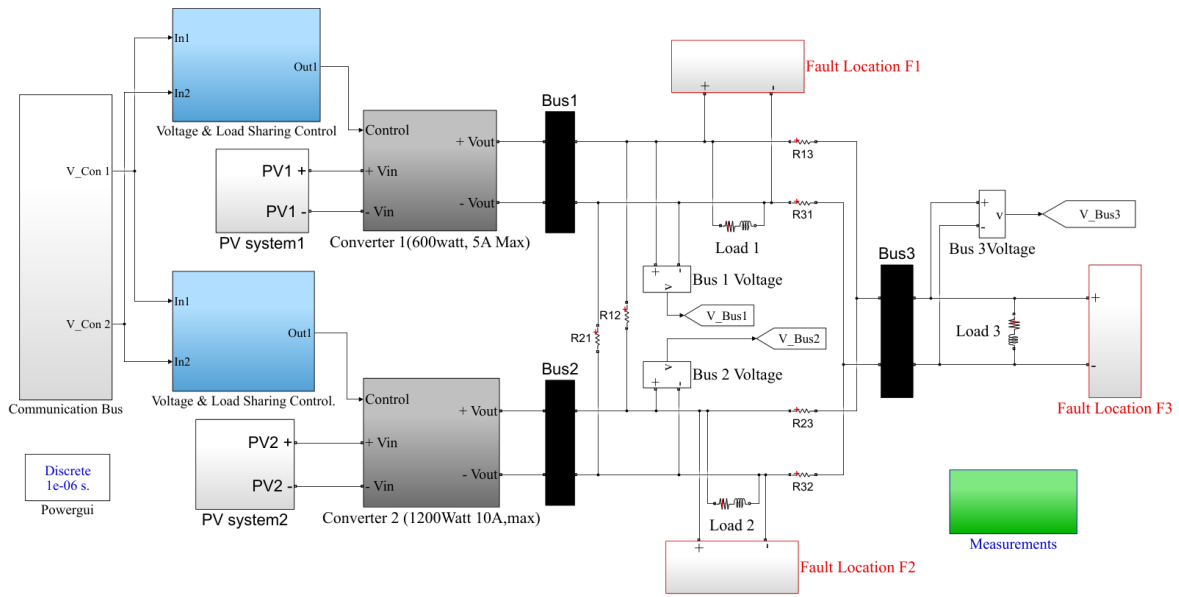


Figure 5.5: Simulink Model to Implement the Proposed C-FCL

5.7 Results and Discussion

This section discusses the results obtained when the ring DC microgrid system (Figure 5.2) was subjected to transient faults at different bus locations and different fault durations to analyze the vulnerability of the system’s control against transient faults and disturbances.

5.7.1 Impact of Short Duration Fault on System Control without FCL

Initially, a small transient short-circuit disturbance of 10 milliseconds was applied at different locations (F_1 , F_2 and F_3 in Figure 5.5) without implementing any type of FCL. It was observed from the results shown in Figure 5.6 (a), that the control system, somehow,

managed to recover the system voltage. However, the power sharing control was affected (Figure 5.6 (b)) and each fault location affects the power sharing control differently.

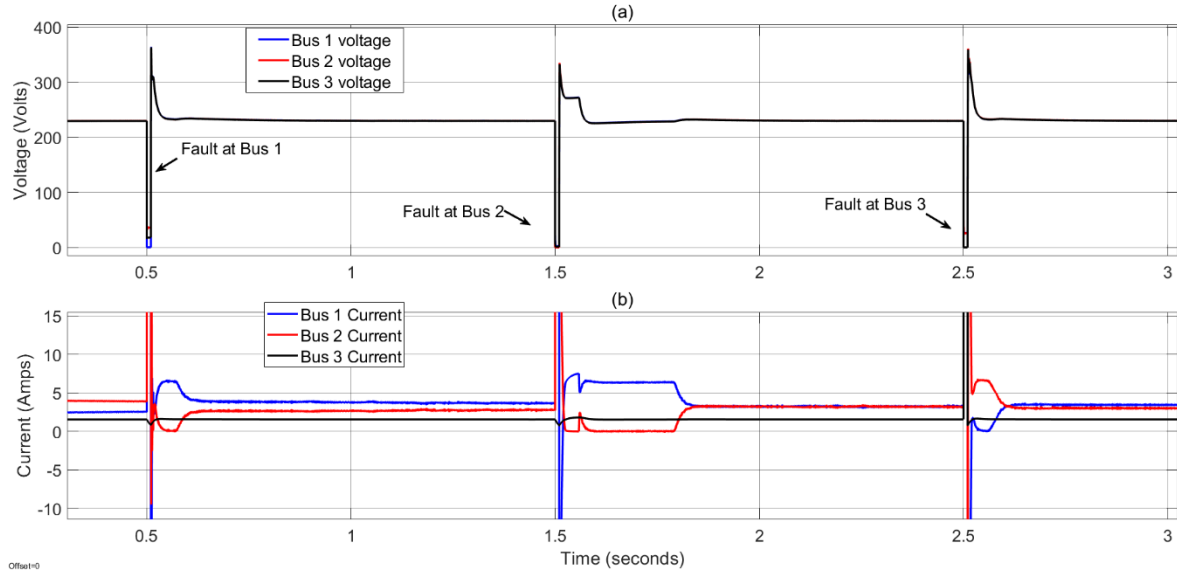


Figure 5.6: Control System Response after a Short Disturbance without FCL

Furthermore, during the fault at bus 1, it was observed that the flow of current continued through bus 3. There was also noticed a flow of current through bus 3 during the fault at bus 2 or 3. After fault clearance in bus 1, the current excess the pre-fault values for a short duration compared to the fault at bus 2. This verified the fact that different fault locations impact the control of power sharing between converters. This is because the impedance of the line that plays a significant role in limiting the fault current varies with fault location. Furthermore, the power sources close to the fault location will contribute more to fault currents and vice versa.

5.7.2 Impact of Long Duration Fault on System Control without FCL

To further analyze the vulnerability of the system control for a bit longer fault duration, a 50-millisecond short-circuit fault was applied at different buses. The response of the system control for a long duration of short-circuit faults at different buses was observed

in Figure 5.7 (a, b). The post-fault current is higher than the normal current (current before the fault), this indicates that there is a bus in the DC microgrid not optimally controlled.

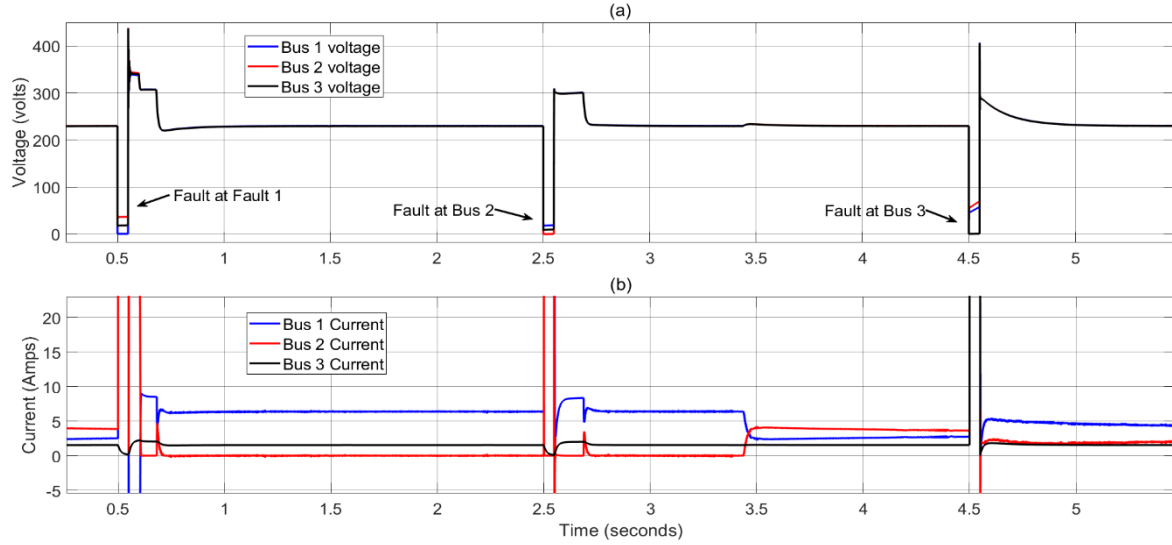


Figure 5.7: Control System Response after a Long Disturbance without FCL

This figure showed that long-duration faults at buses 1 and 2 shifted the converter at bus 2 into the self-protection stage when the fault occurred at bus 1. As a result, the voltage control (Figure 5.7 (a)) and power sharing (Figure 5.7 (b)) were both critically affected, causing a complete system instability. During the blocking stage of the converter at bus 2 as seen in Figure 5.8 (b, c), the system voltage was somehow recovered (see Figure 5.7 (a)). However, the converter at bus 1 was forced to supply the total connected load and became overloaded (Max. current of converter 1 is 5Amps). The PWM control signals to the converters shown in Figure 5.8 (b, c) verified the IGBTs blocking during fault conditions.

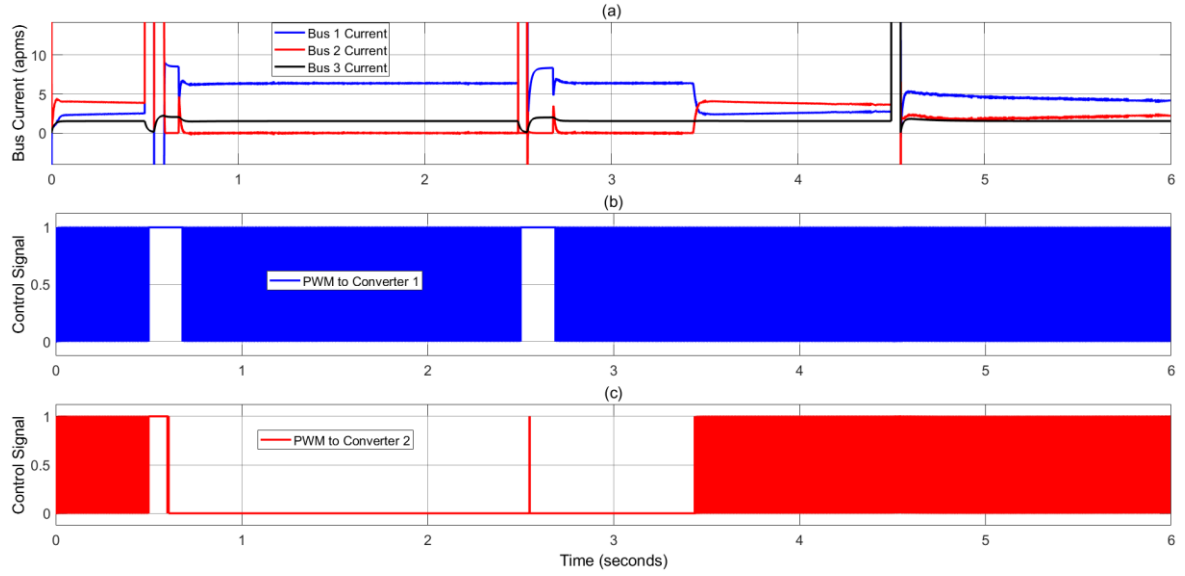


Figure 5.8: PWM Signals to Converters

5.7.3 Control System Response to Short-circuit Fault with Traditional FCL

To mitigate the vulnerability of the control system during fault conditions, a simple solid-state resistive-type FCL was employed in all buses. The appropriate value of FCL in each bus was selected using Equation 5.8 (Section 5.5) to limit the currents of converters to their maximum rated values for different fault locations as given in Table 5.1.

Table 5.1: The Appropriate Values of each FCL w.r.t. Fault Locations

Fault Location	Required Values of Resistances to Limit Fault Currents		
	R_{FCL1}	R_{FCL2}	R_{FCL3}
F1	43	21	0
F2	41	23	0
F3	7.5	3.5	50

It can be noticed from Table 5.1 that the obtained values of the current limiter for fault locations (F₁ and F₂) are almost similar. The reason for this is the applied average

voltage and average current control method in the source buses. This control approach was combined with the circulating current minimization method; hence, the output currents of the controlled converters are synchronously regulated. The slight difference in values is due to the small line resistance between bus 1 and bus 2.

Figure 5.9 shows the obtained results when fixed resistance values of current limiters were selected for fault locations at bus 1 and/or 2 (see Table 5.1). Note that the controllable function of FCL was still not utilized.

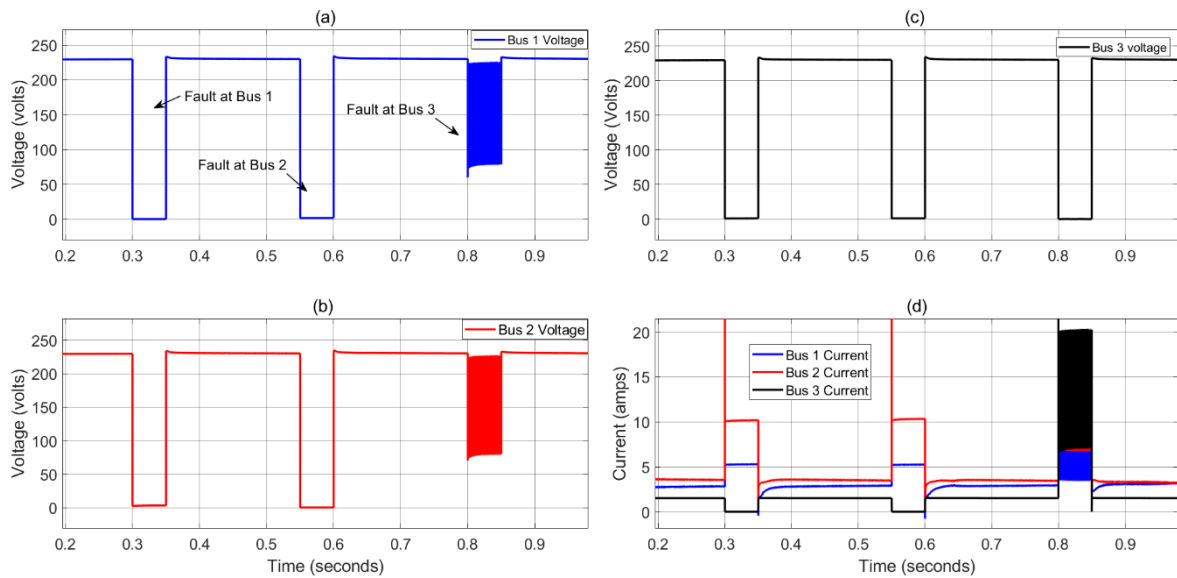


Figure 5.9: Control System Response to Faults at Different Buses when FCL Values were Selected without Controllable Function for Fault Locations F1 and F2 (Figure 5.5)

The results in Figure 5.9 (d) verified that the fixed resistance values of FCL limited the short-circuit currents efficiently during faults at bus 1 and bus 2. However, for the fault location at bus 3, the FCL failed to perform efficiently.

Referring to Figure 5.9, when fault occurs at bus 3, the line resistances are added to the resistive value of current limiters at bus 1 and 2, thus, lowering the fault currents below the maximum rated currents of converters. As a result, the power electronics switches of the

FCL toggle between points A and B (Figure 5.3) during the short-circuit duration, permitting higher spikes of fault currents, thus, partially supplying the fault. The FCLs at bus 1 and 2 were switched OFF when the fault currents were decreased below the rated values and vice versa (Figure 5.9 a, b). The impact of this issue on power sharing control resulted in equal power sharing after fault occurrence at bus 3 (see Figure 5.9 (d)). The zero voltages during faults at bus 1 and bus 2 (Figure 5.9 a, b) indicate that the bus voltages were forced to zero by the FCL at these buses to prevent IGBTs blocking for self-protection as well as to minimize the fault impact on the system.

The output voltages of converters (when traditional FCL was set for fault at bus 1 and 2) are shown in Figure 5.10.

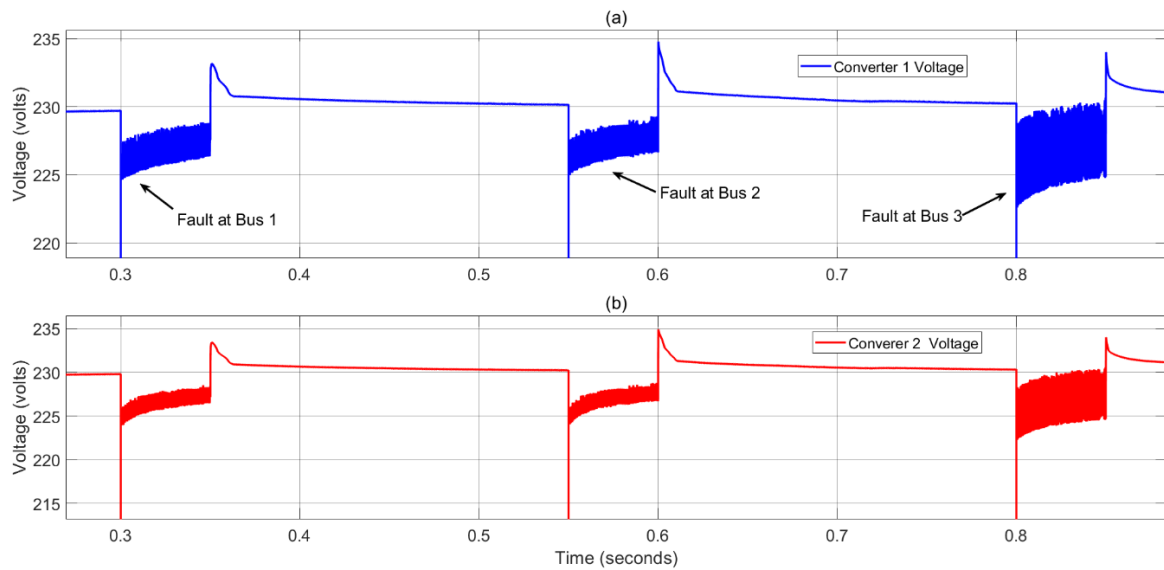


Figure 5.10: Output Voltages of Converters with fixed values of FCL for F_1 & F_2

Figure 5.10 reflected the fact that the selected resistive values of traditional FCL in the buses prevented the IGBTs from blocking during the fault at each location and an acceptable output voltage deviation was seen during the fault at buses 1 and 2, however, during the fault at bus 3, output voltage deviation was significant.

Figure 5.11 shows the response of the system in terms of power sharing control and voltage regulation during fault at different buses when the current limiters values were selected for fault at bus 3.

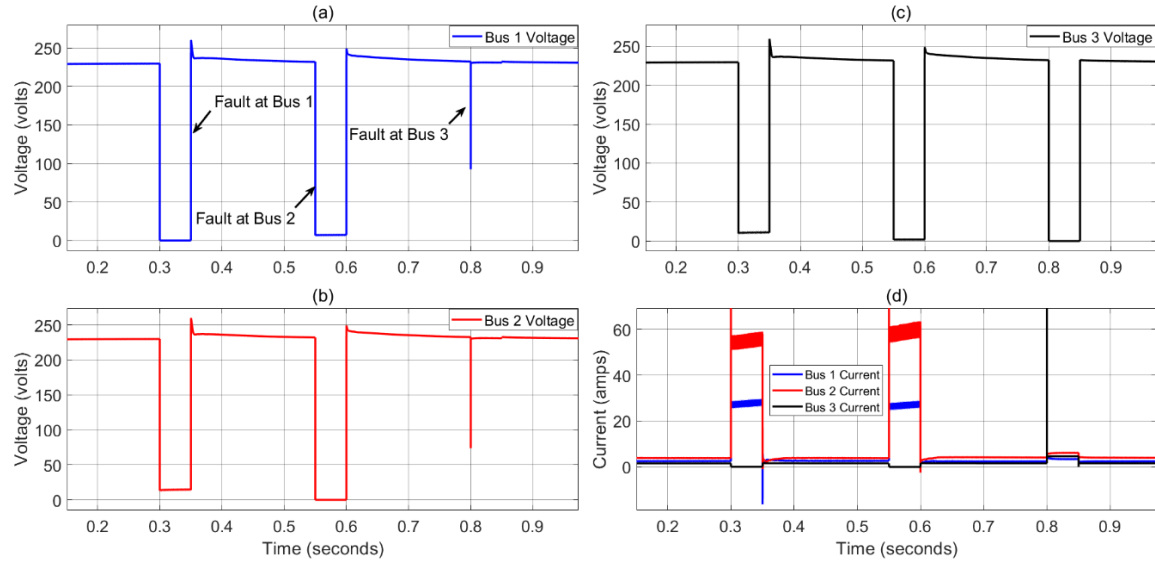


Figure 5.11: System Response to Faults without Controllable Function of FCL

It was observed from the results shown in Figure 5.11 (d) that in this case, the fixed FCL values for fault location at bus 3 (Table 5.1) performed efficiently for fault at bus 3, however, higher fault currents (more than 5 times of the rated values) were observed during faults at bus 1 and 2. Also, a slight impact on voltage control was observed (Figure 5.11 (a, b)) when the fault occurred at bus 1 or bus 2. It was noticed from Figure 5.11 that for each fault location, the FCL prevents the IGBTs blocking, however, the output voltages of converters were impacted significantly during faults at bus 1 and bus 2 as shown in Figure 5.12.

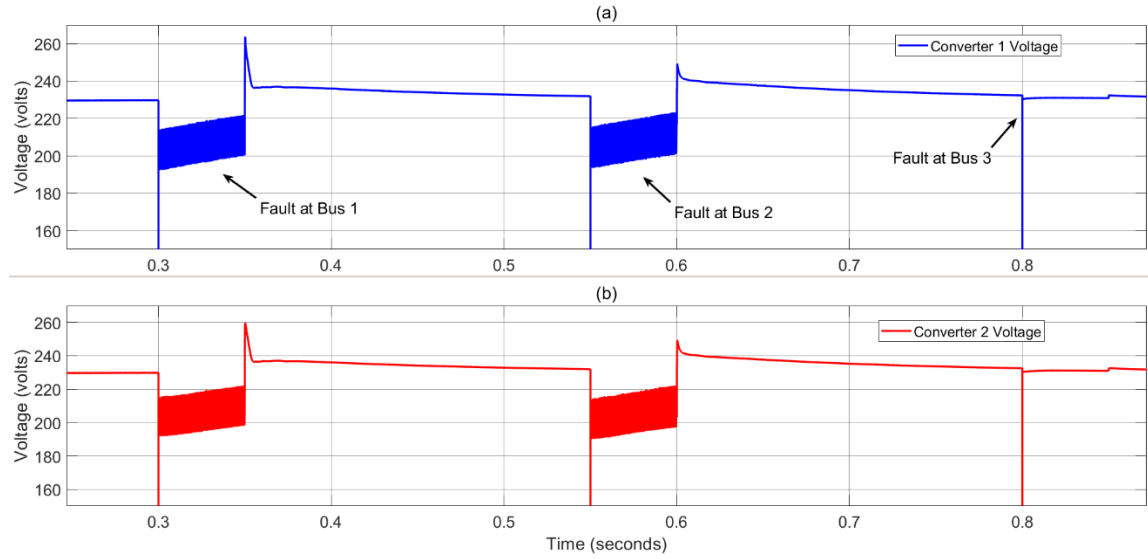


Figure 5.12: Output Voltages of Converters with fixed values of FCL for F_3

5.7.4 Control System Response to Short-circuit Fault with Proposed C-FCL

To address the above-mentioned issues related to the selection of appropriate resistance values to be switched during fault conditions at different locations, the concept of the proposed C-FCL was implemented in each bus. The obtained results shown in Figure 5.13 clearly verified the performance of the proposed fault current limiting scheme.

The results indicated that the resistive value of each C-FCL was accurately controlled to limit the fault current at different fault locations. From Figure 5.13, it was observed that the transient fault currents were efficiently limited irrespective of the fault locations, hence, accurate power sharing and voltage control were maintained. During the faults at bus 1 and bus 2, the bus voltages were dropped to zero by the C-FCL to avoid the negative impact of the fault on the system and the supply to connected loads was temporarily disconnected only for the fault duration, however, the output voltages of converters were quietly stable during the fault conditions for each fault location (see Figure 5.14).

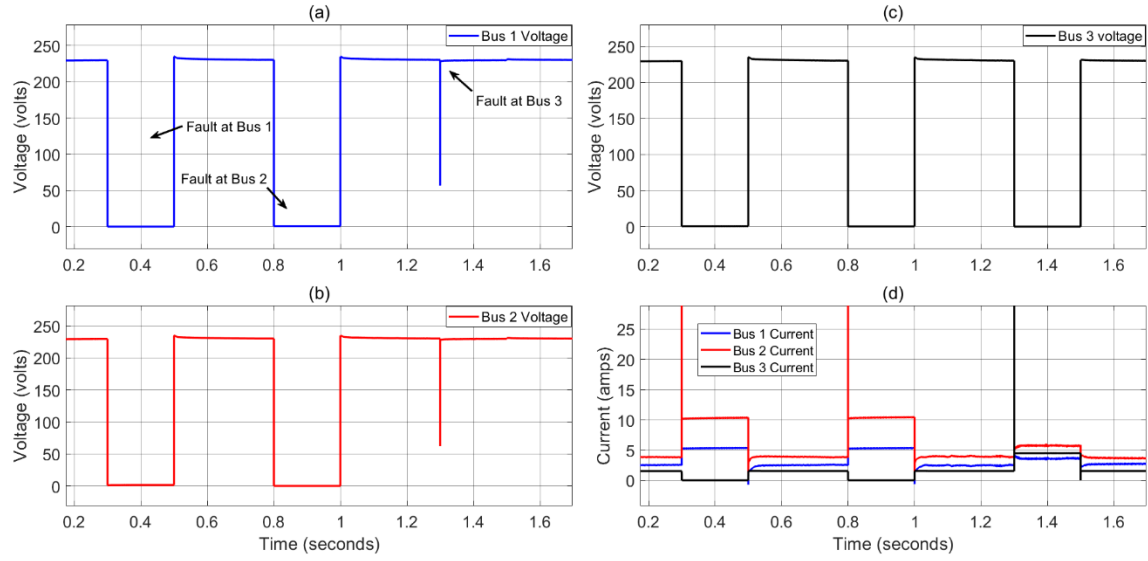


Figure 5.13: System Response to Faults at Different Buses using Proposed C-FCL

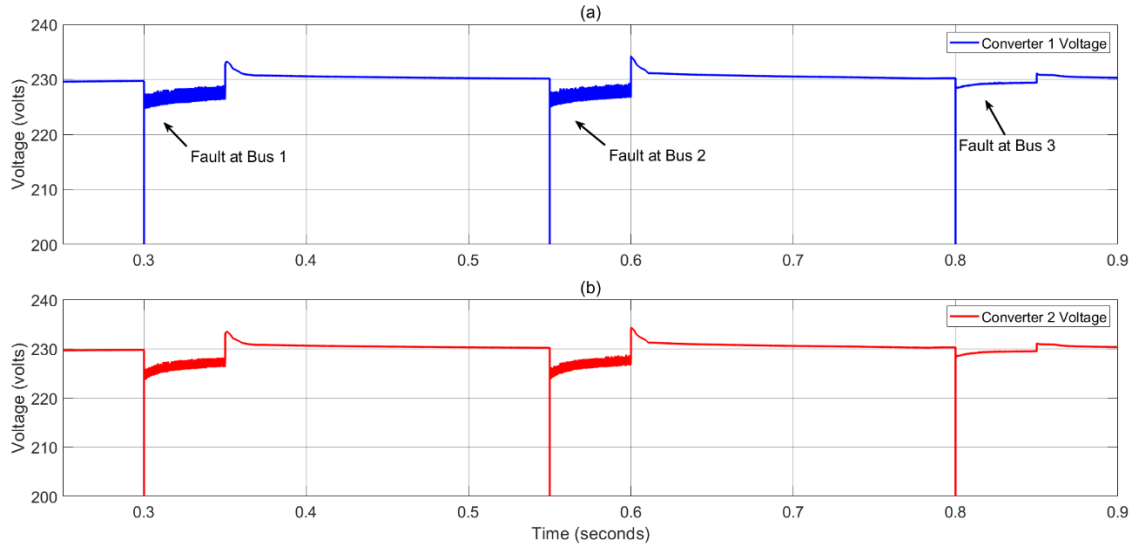


Figure 5.14: Output Voltages of Converters with Proposed C-FCL

It is worth noticing that during the fault at bus 3, the C-FCL used in bus 1 and bus 2 did not force the bus voltage to zero and the loads connected to bus 1 and bus 2 continued receiving power supply normally. Furthermore, during the fault at bus 3, the power sharing control was not disturbed, and the converters were operating below the maximum rated currents (see Figure 5.13 (d)).

To further verify the performance of the proposed C-FCL, long duration short-circuit faults of 200 milli-seconds were applied at different fault locations, assuming a coordination delay in the protection system. The system response to long duration faults is shown in Figure 5.15. The results proved that the proposed C-FCL is capable of mitigating the vulnerability of system control against short-circuit faults irrespective of the fault duration and fault location.

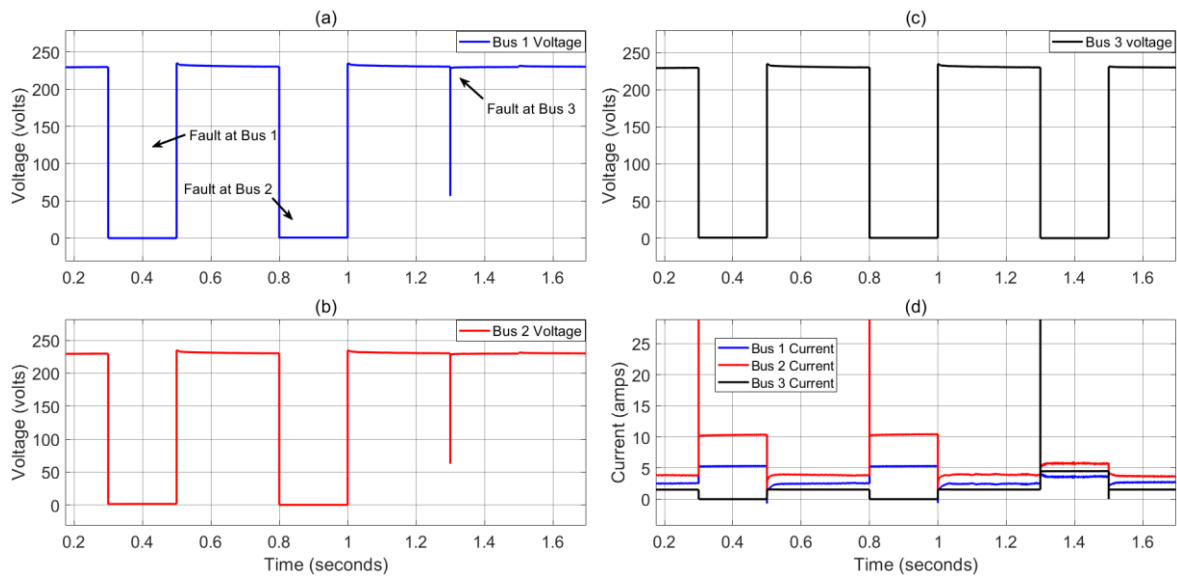


Figure 5.15: System Response to Long Duration Faults using Proposed C-FCL

The presented results in Chapter “5” clearly state what existing problems are solved, and what is the benchmark with respect to which the claimed improvements have been achieved. For instance, the results in Section 5.7 demonstrate different scenarios that represent three DC microgrid systems. The first system is the DC microgrid with no fault current limiter; the second system is a DC microgrid with a traditional fault current limiter; the third system is a DC microgrid with a controllable fault current limiter. Limiting the transient fault current by which post-fault voltage is maintained at the acceptable level ($\pm 5\%$) is utilized as a benchmark to validate the performance of the proposed approach [157], [158].

Here, no impact on power sharing control should occur during fault conditions. The significant results are depicted in Table 5.2, which summarizes the improvements achieved in fulfilling the electric utilities benchmark requirements.

Table 5.2: Benchmark validation of the proposed C-FCL method

DC microgrid operation	Fault location in DC microgrid									Acceptable post-fault
	Bus (1)			Bus (2)			Bus (3)			
	Percentage increase (+) or decrease (-) of post-fault voltage (%)									
	Bus1	Bus2	Bus3	Bus1	Bus2	Bus3	Bus1	Bus2	Bus3	
without FCL	+32 0	+23 0	+17 0	+32 0	+23 0	+17 0	+32 0	+23 0	+17 0	5
with traditional FCL	+1.9 -2.6	+2.13 -2.22	+1.9 - 3.13	+1.9 -2.6	+2.13 -2.22	+1.9 -3.13	+11.5 -17.4	+8 -17	+0.86 -0.15	
with C-FCL	+0.86 -0.87	+0.9 -0.86	+0.4 -0.43	+0.86 -0.87	+0.9 -0.86	+0.4 -0.43	+0.86 -0.87	+0.9 -0.86	+0.4 -0.43	

5.8 Chapter Summary

The proposed fast preventive scheme based on a controllable short current limiter is capable of mitigating the destructive effects of transient short-circuit faults and the loss of DC microgrid control. Usually, the IGBT switches of power converters are blocked for self-protection when the fault at a DC microgrid starts, causing instability of grid control. In this sense, the proposed C-FCL is capable of limiting the fault current magnitudes in different locations, keeping the IGBTs operating in safe mode while implementing power sharing

control and voltage regulation. The main advantages of the proposed C-FCL are the fast response as it uses the local bus voltage and current to adjust the limiter; and the simplicity in coordinating its function with the power sharing control and voltage regulation during fault conditions at any location.

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

This thesis briefly concluded that the integration of RES can produce adverse effects, particularly on a power system's stability, power quality and reliability. Power intermittency of RES, switching of power converters, penetration level, and the location of RES are the key factors that contribute to such issues. Further, DC microgrids with the LVDC distribution system provide better and simpler control, lower power losses, better efficiency, and economical use of RES, especially in remote areas.

From the results, it was concluded that applying DC voltage equal to the peak value of AC waveform reduces the power loss to half value compared to AC microgrid and the voltage drop in the distribution lines reduces by 29.3%. From an economic point of view, it was concluded that the DC microgrid is affordable and cheaper than the conventional AC microgrid. This is due to the smaller number of conversion stages and reduced overall cost of the system. However, DC microgrids and DC distribution systems still lack common standards in terms of domestic and commercial applications worldwide. In addition, the proposed distributed control strategy for DC microgrids has better voltage regulation performance with higher power sharing accuracy, and fast system response with lower voltage deviations due to load switching. Furthermore, the tap change control of the microgrid reference voltage can help in reducing the power distribution losses during overload conditions, as a result, increasing DC microgrid reliability.

From the dynamic analysis, it was concluded that short-circuit faults in DC microgrids produce higher magnitudes of fault currents compared to AC microgrids for the same voltage and power levels, hence, DC systems are more vulnerable to transient disturbances and faults. Moreover, the protection of DC systems has not been developed as compared to AC protection systems. In this scene, the proposed C-FCL efficiently limits the fault current magnitudes in different bus locations, keeping the microgrid operating safely and minimizing the impact of fault on power sharing control and voltage regulation. Therefore, it can be concluded that the stability issues during transient disturbances and faults require careful attention when designing the DC microgrids.

6.2 Future Research Areas

With the expansion of distributed generation from RES and common challenges of integration, it is observed that the adoption of the DC microgrids in the present power grid is crucial as one of the suitable solutions for power quality compensation and grid integration issues. It is foreseeable that the DC system will be the norm in the future electricity grid. Accordingly, the main future research paths inferred from this thesis are:

- i. The main challenge that hinders the expansion of DC microgrids installation is the lack of guidelines and standards for DC systems. Hence, the development of common standards for steady-state and transient conditions is essential for the practical implementation of DC microgrids.
- ii. Development of intelligent coordination and more robust control techniques to perform better accuracy in energy optimization.

- iii. The conventional protection schemes may not solve the DC microgrid protection issues. Therefore, advanced DC circuit breakers and controllable current limiting technologies must be considered comprehensively to facilitate the wide adoption of DC microgrids.

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- [159] Yang M., Xin C., Hongpeng J., Liang J., Yang F., Chengshan W., Jianhui W. (2019). The coordinated control strategy for isolated DC microgrid based on adaptive storage adjustment without communication. *Applied Energy*, 252, 1-12.
- [160] Veysi M., Jamshid A., Reza M. S., Mokhtar S., Behrooz B., Daniel J. R. (2022). Robust, Accurate, and Fast Decentralized Power Sharing Mechanism for Isolated DC Microgrid Using Droop-Based Sliding-Mode Control. *IEEE Transactions on Smart Grid*, 13(6), 4160-4173.

APPENDICES

LIST OF PUBLICATIONS

- [1] Shahid, U., Ahmed, M. A. H., & Hushairi, Z. (2020). Assessment of technical and financial benefits of AC and DC microgrids based on solar photovoltaic. *Electrical Engineering*, 1-14.

- [2] Shahid, U., Ahmed, M. A. H., Paul, H. & Hushairi, Z., & Ahfock, T. (2020). The Current State of Distributed Renewable Generation, Challenges of Interconnection and Opportunities for Energy Conversion based DC Microgrids. *Journal of Cleaner Production*, 273.

- [3] Shahid, U., Ahmed, M. A. H., Muttaqi, K. M. & Ahfock, T. (2019). A Distributed Secondary Control Strategy for Power Sharing and Voltage Regulation by Multiple Converters in DC Micro-grids. In: IEEE, *1st International Conference on Electrical, Control and Instrumentation Engineering (ICECIE)*, Kuala Lumpur, Malaysia, 25 November 2019.

APPENDICES

SYSTEM SIMULATION REPORT AC/AC



System Simulation Report



File: PV_AC_LOAD_AC.homer

Author:

Location: Bario STOLport, Bario Airport, Sarawak, 98800 Bario, Malaysia (3°44.1'N, 115°28.8'E)

Total Net Present Cost: RM49,050.14

Levelized Cost of Energy (RM/kWh): RM0.924

Notes: PV_AC_LOAD_AC



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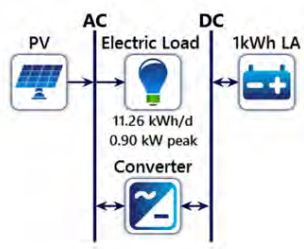
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System Architecture

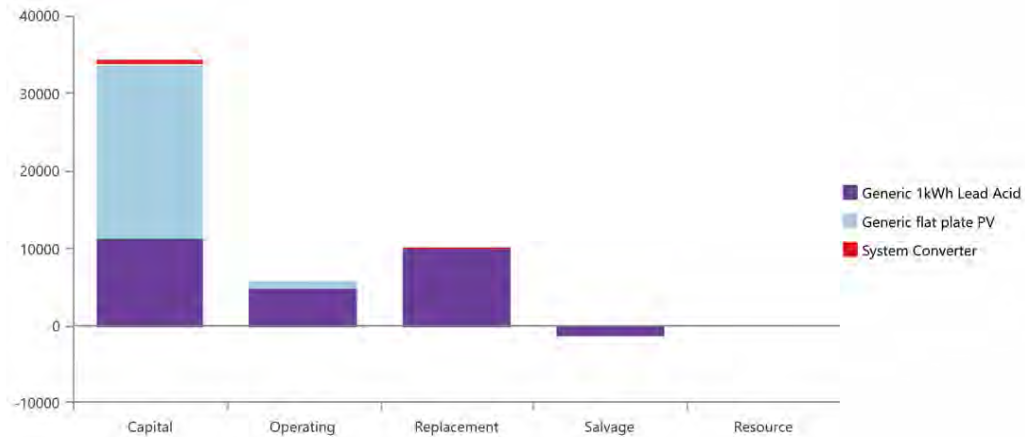
Component	Name	Size	Unit
PV	Generic flat plate PV	7.44	kW
Storage	Generic 1kWh Lead Acid	38	strings
System converter	System Converter	1.83	kW
Dispatch strategy	HOMER Load Following		

Schematic





Cost Summary



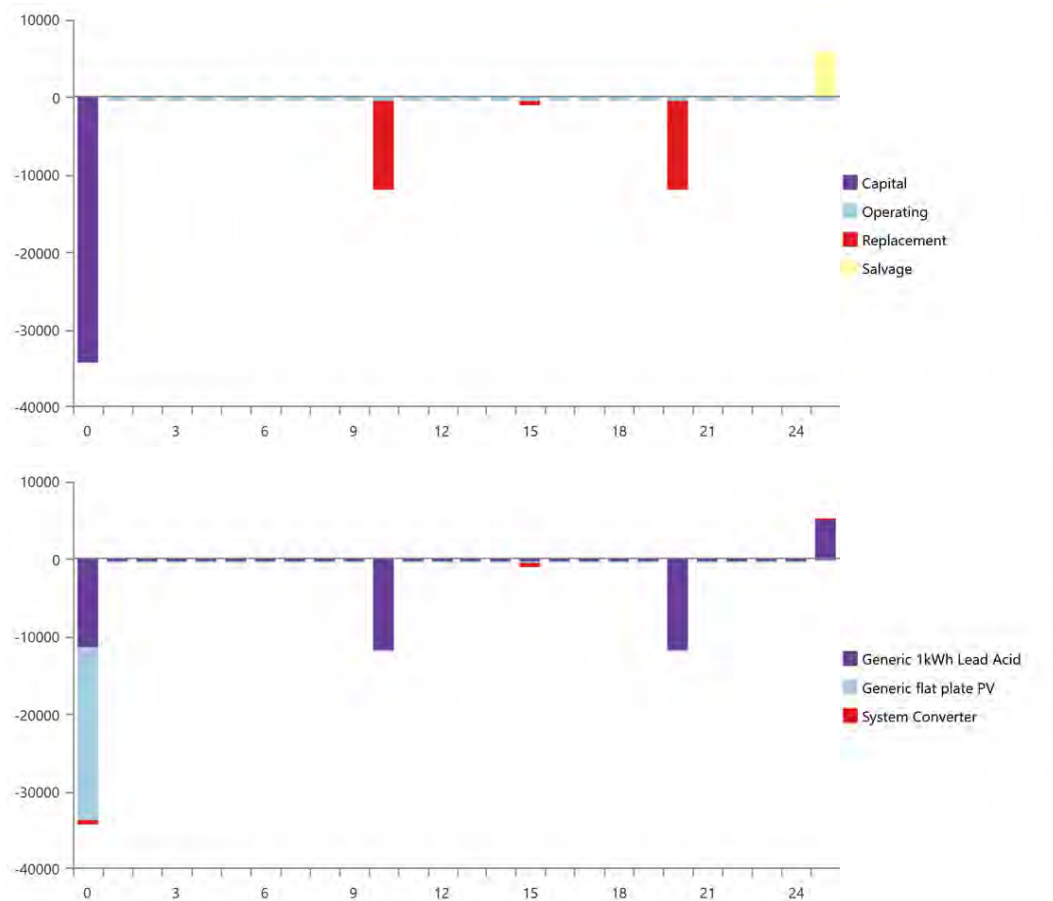
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Lead Acid	RM11,400	RM4,912	RM10,071	-RM1,365	RM0.00	RM25,018
Generic flat plate PV	RM22,333	RM962.35	RM0.00	RM0.00	RM0.00	RM23,295
System Converter	RM548.27	RM0.00	RM232.62	-RM43.78	RM0.00	RM737.11
System	RM34,281	RM5,875	RM10,304	-RM1,409	RM0.00	RM49,050

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Lead Acid	RM881.84	RM380.00	RM779.05	-RM105.63	RM0.00	RM1,935
Generic flat plate PV	RM1,728	RM74.44	RM0.00	RM0.00	RM0.00	RM1,802
System Converter	RM42.41	RM0.00	RM17.99	-RM3.39	RM0.00	RM57.02
System	RM2,652	RM454.44	RM797.04	-RM109.01	RM0.00	RM3,794

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	5,639	kWh/yr
Unmet Electric Load	3.30	kWh/yr
Capacity Shortage	4.09	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	10,717	100
Total	10,717	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	4,106	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	4,106	100



PV: Generic flat plate PV

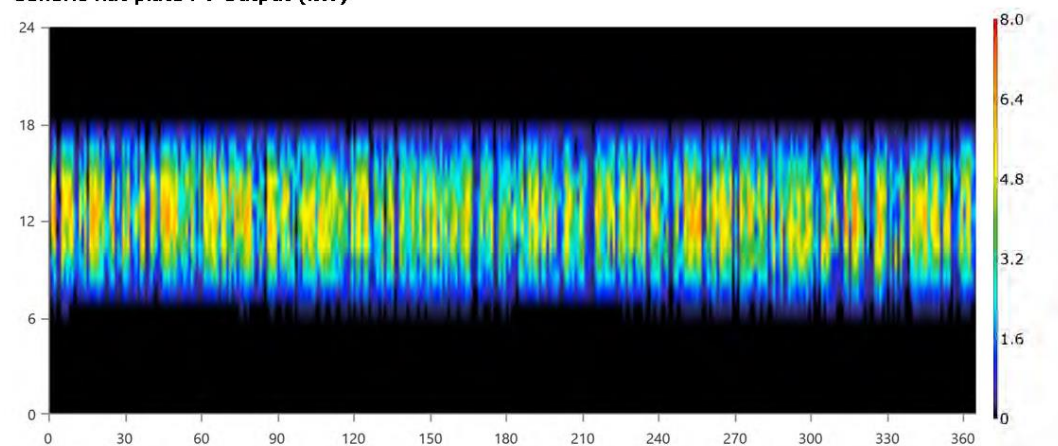
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	7.17	kW
PV Penetration	261	%
Hours of Operation	4,324	hrs/yr
Levelized Cost	0.168	RM/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	7.44	kW
Mean Output	1.22	kW
Mean Output	29.4	kWh/d
Capacity Factor	16.4	%
Total Production	10,717	kWh/yr

Generic flat plate PV Output (kW)





Storage: Generic 1kWh Lead Acid

Generic 1kWh Lead Acid Properties

Quantity	Value	Units
Batteries	38.0	qty.
String Size	1.00	batteries
Strings in Parallel	38.0	strings
Bus Voltage	12.0	V

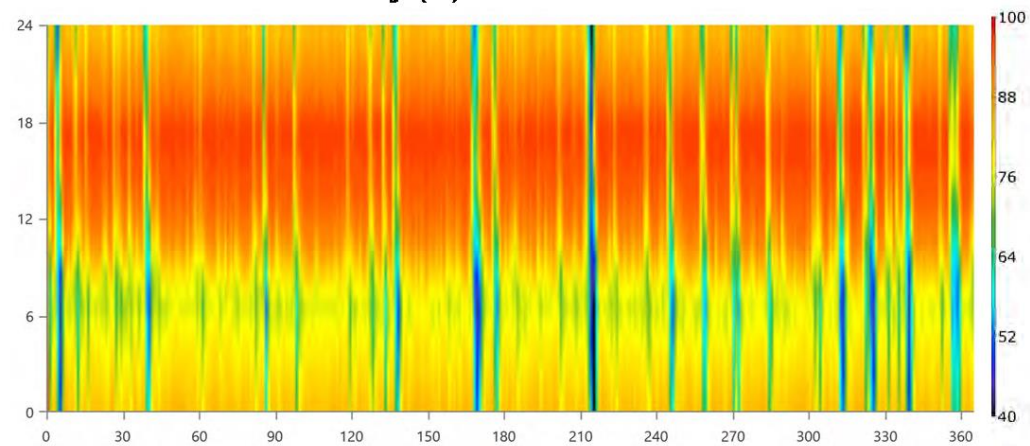
Generic 1kWh Lead Acid Result Data

Quantity	Value	Units
Average Energy Cost	0	RM/kWh
Energy In	3,340	kWh/yr
Energy Out	2,678	kWh/yr
Storage Depletion	6.35	kWh/yr
Losses	669	kWh/yr
Annual Throughput	2,994	kWh/yr

Generic 1kWh Lead Acid Statistics

Quantity	Value	Units
Autonomy	48.6	hr
Storage Wear Cost	0.419	RM/kWh
Nominal Capacity	38.0	kWh
Usable Nominal Capacity	22.8	kWh
Lifetime Throughput	29,942	kWh
Expected Life	10.0	yr

Generic 1kWh Lead Acid State of Charge (%)





Converter: System Converter

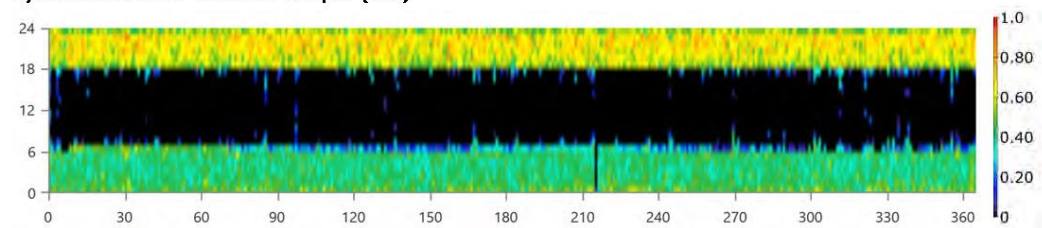
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	5,001	hrs/yr
Energy Out	2,544	kWh/yr
Energy In	2,678	kWh/yr
Losses	134	kWh/yr

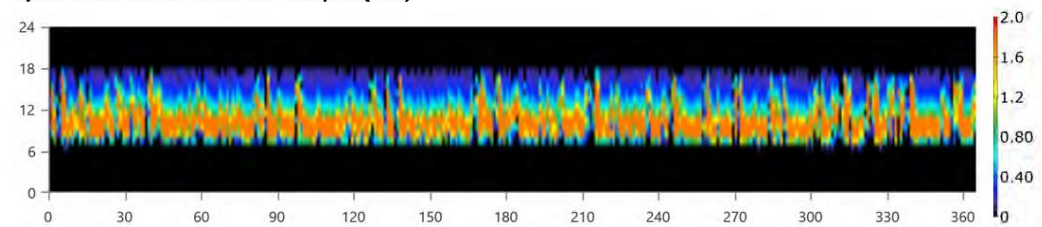
System Converter Statistics

Quantity	Value	Units
Capacity	1.83	kW
Mean Output	0.290	kW
Minimum Output	0	kW
Maximum Output	0.897	kW
Capacity Factor	15.9	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)

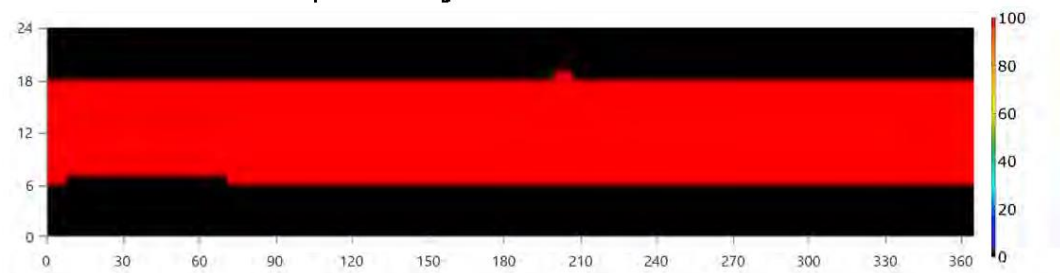




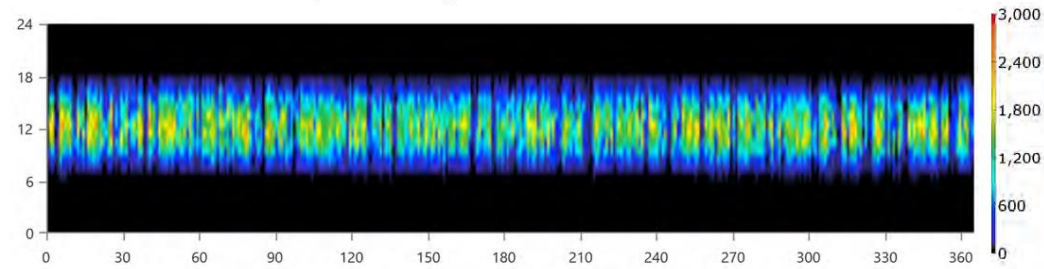
Renewable Summary

Capacity-based metrics		Value	Unit
Nominal renewable capacity divided by total nominal capacity		100	%
Usable renewable capacity divided by total capacity		100	%
Energy-based metrics		Value	Unit
Total renewable production divided by load		261	%
Total renewable production divided by generation		100	%
One minus total nonrenewable production divided by load		100	%
Peak values		Value	Unit
Renewable output divided by load (HOMER standard)		2,685	%
Renewable output divided by total generation		100	%
One minus nonrenewable output divided by total load		100	%

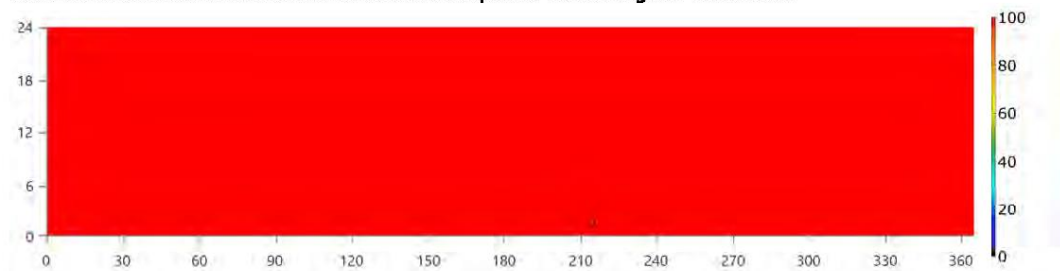
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load





Compare Economics

IRR (%):**N/A**

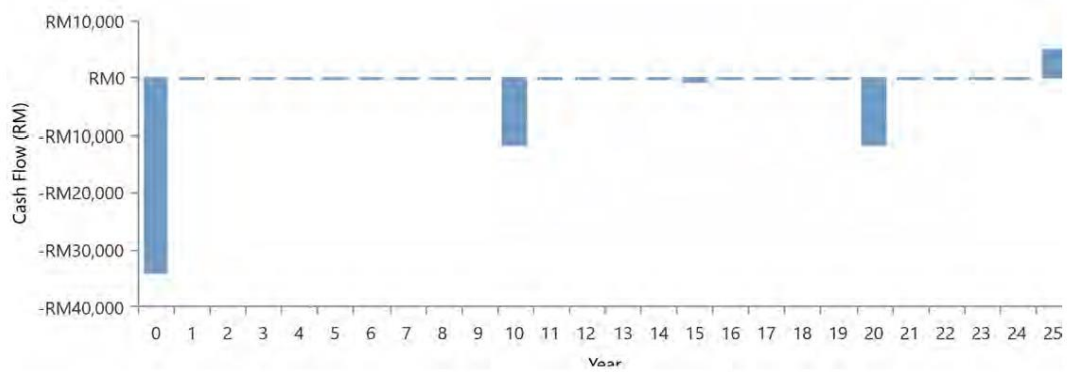
Discounted payback (yr):**N/A**

Simple payback (yr):**N/A**

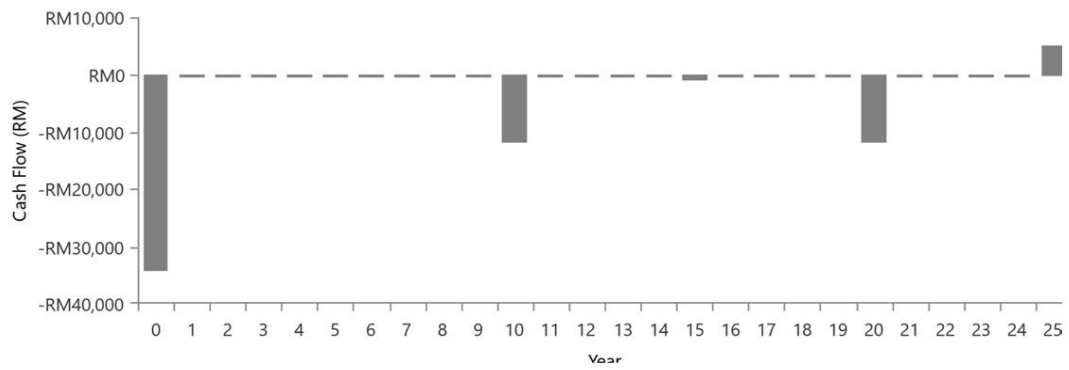
	Base System	Proposed System
Net Present Cost	RM49,050	RM49,050
CAPEX	RM34,281	RM34,281
OPEX	RM1,142	RM1,142
LCOE (per kWh)	RM0.924	RM0.924
CO2 Emitted (kg/yr)	0	0
Fuel Consumption (L/yr)	0	0



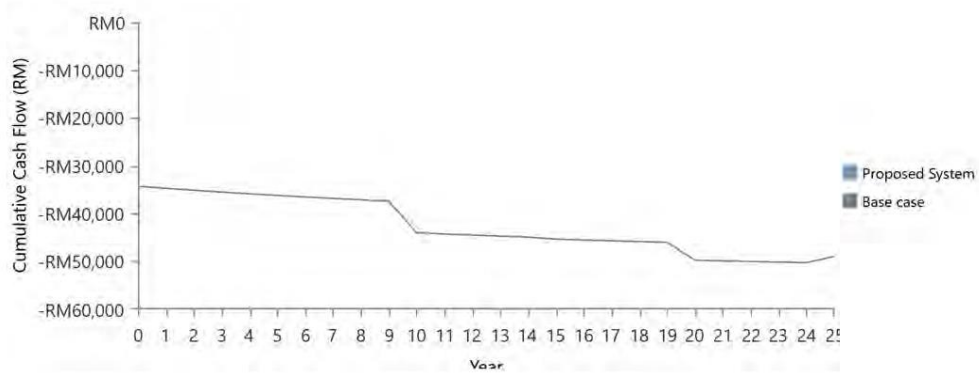
Proposed Annual Nominal Cash Flows



Base System Annual Nominal Cash Flows

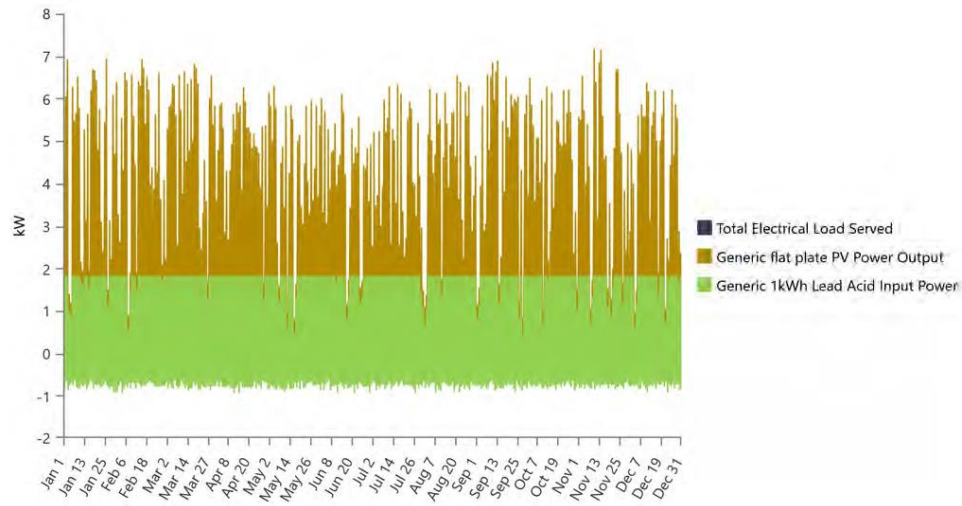


Cumulative Discounted Cash Flows





Time series charts:



APPENDICES

SYSTEM SIMULATION REPORT DC/AC



System Simulation Report



File: PV_DC_LOAD_AC.homer

Author:

Location: Bario STOLport, Bario Airport, Sarawak, 98800 Bario, Malaysia (3°44.1'N, 115°28.8'E)

Total Net Present Cost: RM48,776.03

Levelized Cost of Energy (RM/kWh): RM0.919

Notes: PV_DC_LOAD_AC



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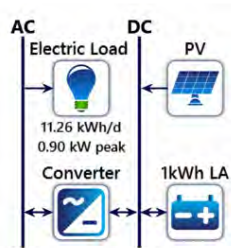
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System Architecture

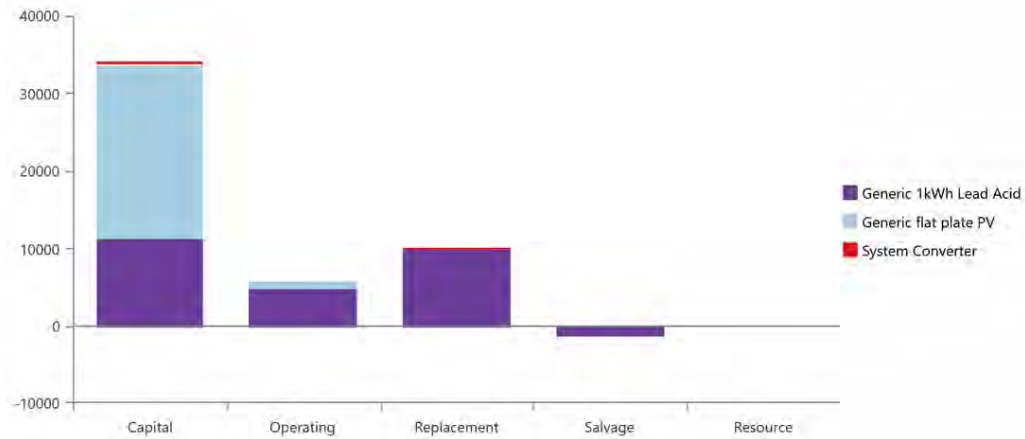
Component	Name	Size	Unit
PV	Generic flat plate PV	7.46	kW
Storage	Generic 1kWh Lead Acid	38	strings
System converter	System Converter	1.02	kW
Dispatch strategy	HOMER Load Following		

Schematic





Cost Summary



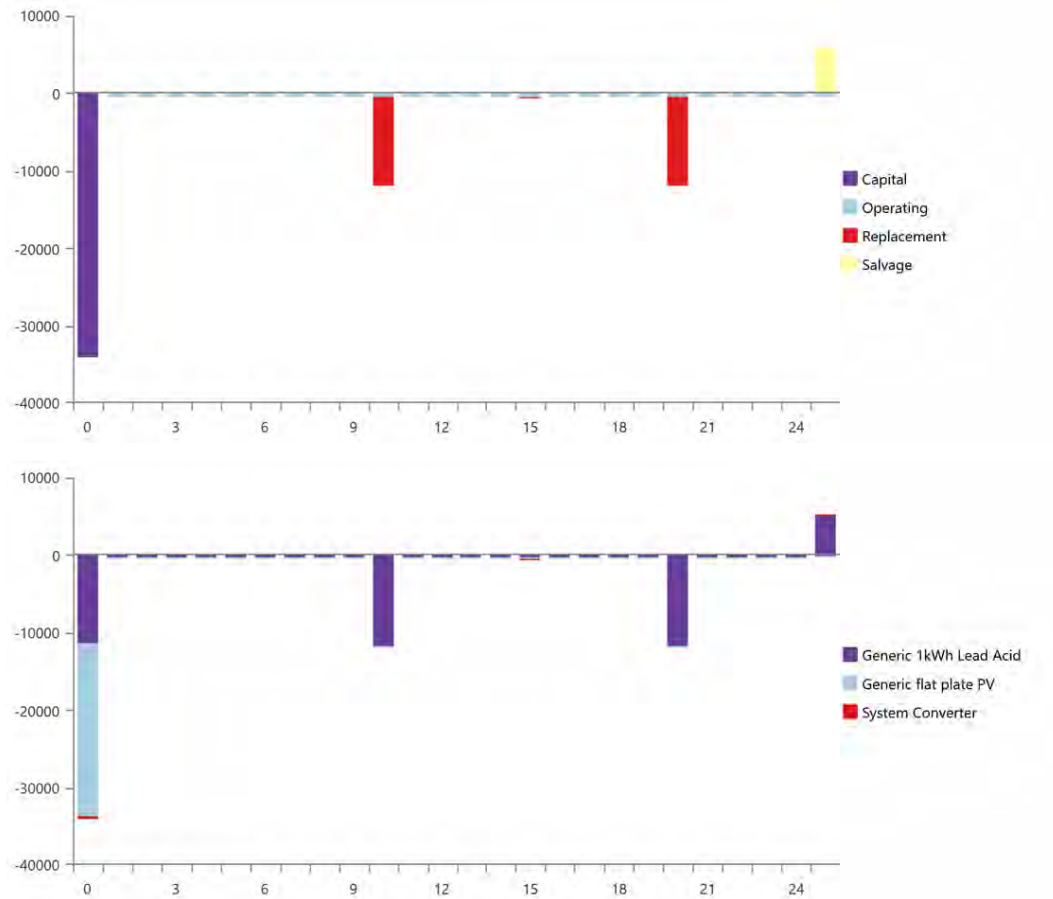
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Lead Acid	RM11,400	RM4,912	RM10,071	-RM1,365	RM0.00	RM25,018
Generic flat plate PV	RM22,380	RM964.41	RM0.00	RM0.00	RM0.00	RM23,345
System Converter	RM307.22	RM0.00	RM130.34	-RM24.53	RM0.00	RM413.03
System	RM34,088	RM5,877	RM10,202	-RM1,390	RM0.00	RM48,776

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Lead Acid	RM881.84	RM380.00	RM779.05	-RM105.63	RM0.00	RM1,935
Generic flat plate PV	RM1,731	RM74.60	RM0.00	RM0.00	RM0.00	RM1,806
System Converter	RM23.76	RM0.00	RM10.08	-RM1.90	RM0.00	RM31.95
System	RM2,637	RM454.60	RM789.13	-RM107.52	RM0.00	RM3,773

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	5,753	kWh/yr
Unmet Electric Load	3.30	kWh/yr
Capacity Shortage	4.10	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	10,740	100
Total	10,740	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	4,106	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	4,106	100



PV: Generic flat plate PV

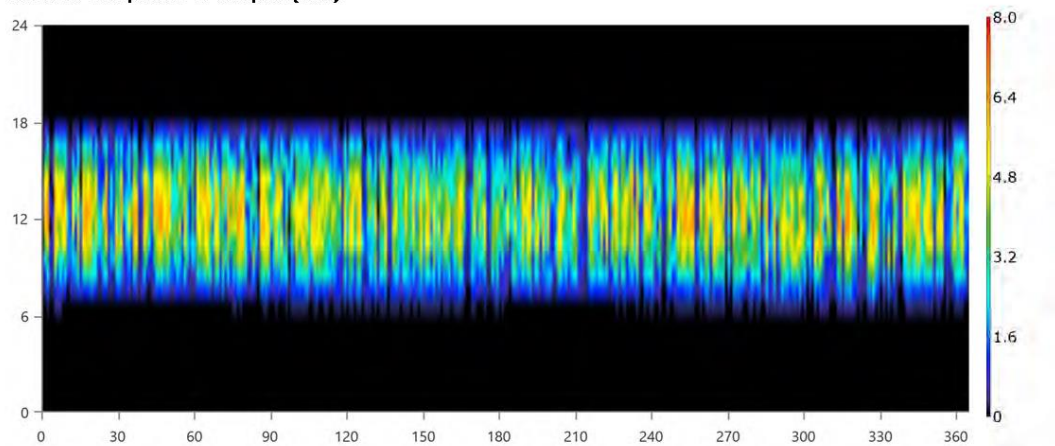
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	7.19	kW
PV Penetration	261	%
Hours of Operation	4,324	hrs/yr
Levelized Cost	0.168	RM/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	7.46	kW
Mean Output	1.23	kW
Mean Output	29.4	kWh/d
Capacity Factor	16.4	%
Total Production	10,740	kWh/yr

Generic flat plate PV Output (kW)





Storage: Generic 1kWh Lead Acid

Generic 1kWh Lead Acid Properties

Quantity	Value	Units
Batteries	38.0	qty.
String Size	1.00	batteries
Strings in Parallel	38.0	strings
Bus Voltage	12.0	V

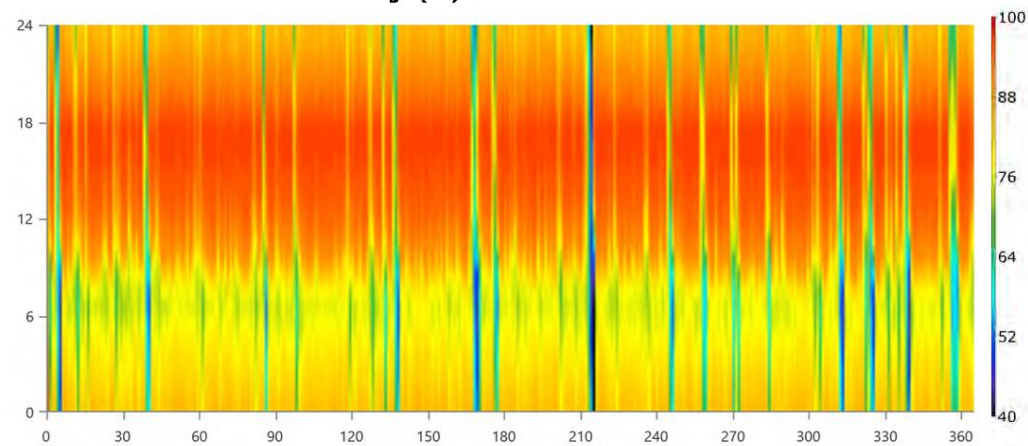
Generic 1kWh Lead Acid Result Data

Quantity	Value	Units
Average Energy Cost	0	RM/kWh
Energy In	3,350	kWh/yr
Energy Out	2,685	kWh/yr
Storage Depletion	6.21	kWh/yr
Losses	671	kWh/yr
Annual Throughput	3,002	kWh/yr

Generic 1kWh Lead Acid Statistics

Quantity	Value	Units
Autonomy	48.6	hr
Storage Wear Cost	0.419	RM/kWh
Nominal Capacity	38.0	kWh
Usable Nominal Capacity	22.8	kWh
Lifetime Throughput	30,023	kWh
Expected Life	10.0	yr

Generic 1kWh Lead Acid State of Charge (%)





Converter: System Converter

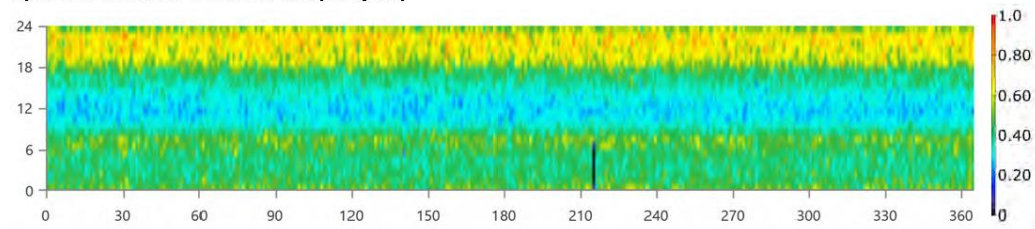
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	8,759	hrs/yr
Energy Out	4,106	kWh/yr
Energy In	4,322	kWh/yr
Losses	216	kWh/yr

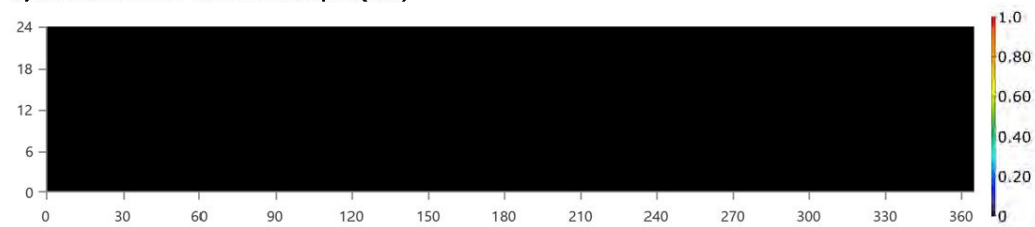
System Converter Statistics

Quantity	Value	Units
Capacity	1.02	kW
Mean Output	0.469	kW
Minimum Output	0	kW
Maximum Output	0.897	kW
Capacity Factor	45.8	%

System Converter Inverter Output (kW)



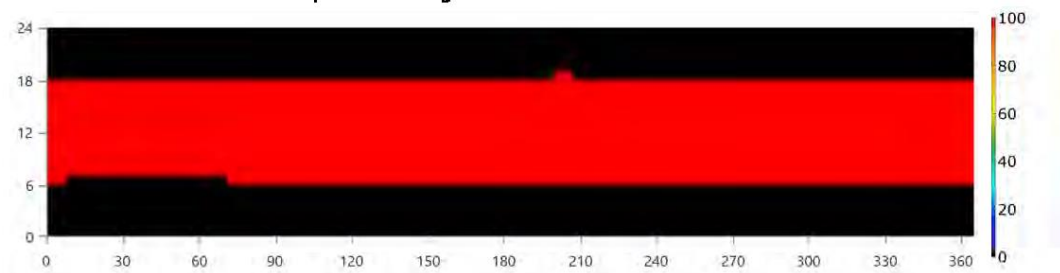
System Converter Rectifier Output (kW)



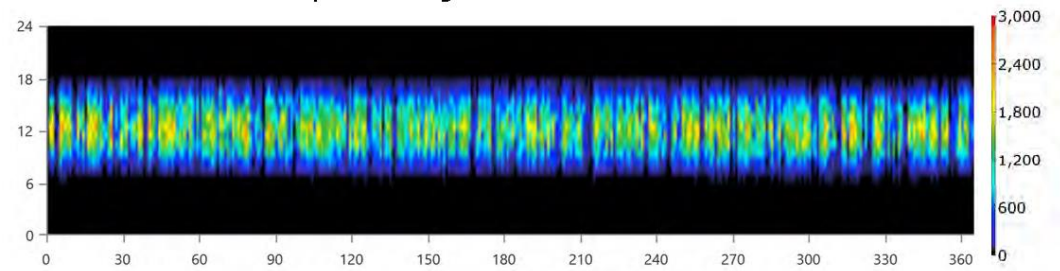
Renewable Summary

Capacity-based metrics		Value	Unit
Nominal renewable capacity divided by total nominal capacity		100	%
Usable renewable capacity divided by total capacity		100	%
Energy-based metrics		Value	Unit
Total renewable production divided by load		262	%
Total renewable production divided by generation		100	%
One minus total nonrenewable production divided by load		100	%
Peak values		Value	Unit
Renewable output divided by load (HOMER standard)		2,691	%
Renewable output divided by total generation		100	%
One minus nonrenewable output divided by total load		100	%

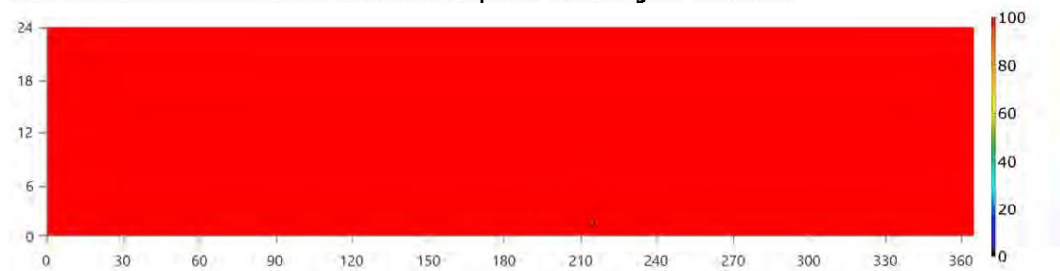
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load





Compare Economics

IRR (%): **N/A**

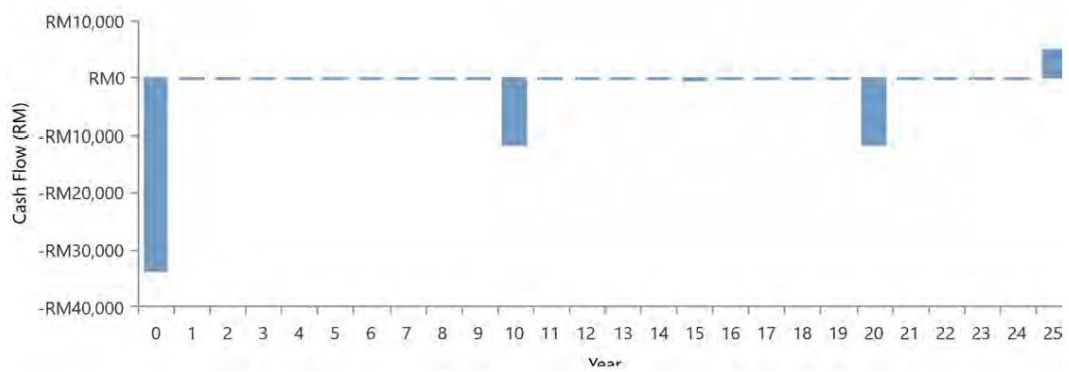
Discounted payback (yr): **N/A**

Simple payback (yr): **N/A**

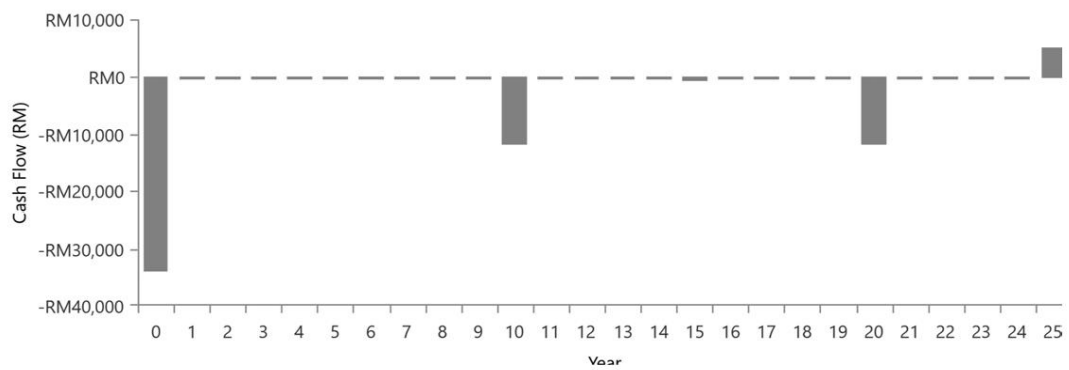
	Base System	Proposed System
Net Present Cost	RM48,776	RM48,776
CAPEX	RM34,088	RM34,088
OPEX	RM1,136	RM1,136
LCOE (per kWh)	RM0.919	RM0.919
CO2 Emitted (kg/yr)	0	0
Fuel Consumption (L/yr)	0	0



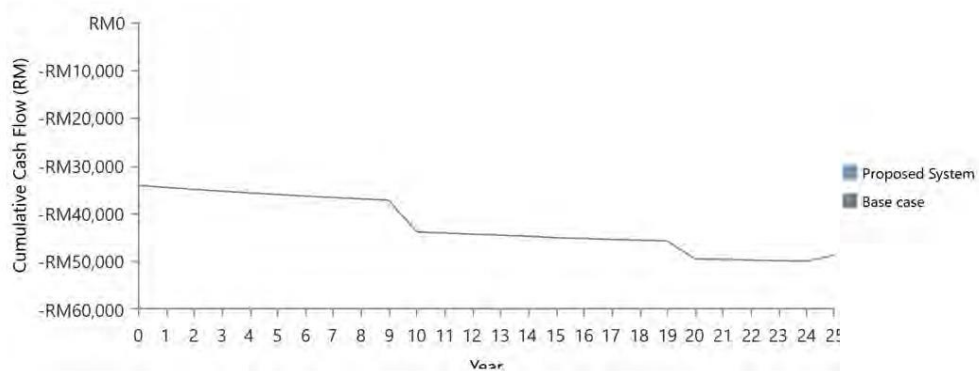
Proposed Annual Nominal Cash Flows



Base System Annual Nominal Cash Flows

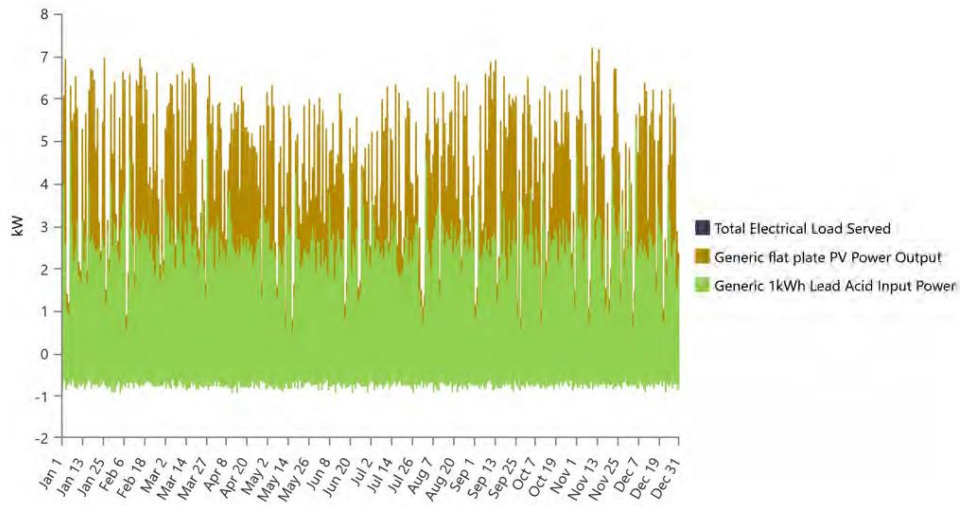


Cumulative Discounted Cash Flows





Time series charts:



APPENDICES

SYSTEM SIMULATION REPORT DC/DC



System Simulation Report



File: PV_DC_LOAD_DC.homer

Author:

Location: Bario STOLport, Bario Airport, Sarawak, 98800 Bario, Malaysia (3°44.1'N, 115°28.8'E)

Total Net Present Cost: RM47,085.68

Levelized Cost of Energy (RM/kWh): RM0.887

Notes: PV_DC_LOAD_DC



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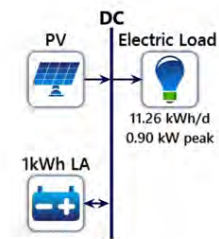
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Storage: Generic 1kWh Lead Acid	8
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Compare Economics	10
Time series charts:	12
Time series charts:	13
Time series charts:	14
Time series charts:	15
Time series charts:	16
Time series charts:	17



System Architecture

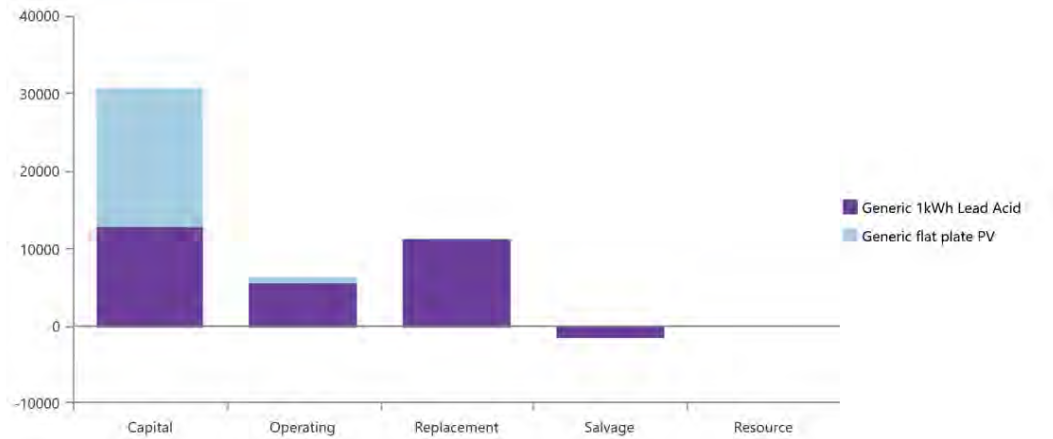
Component	Name	Size	Unit
PV	Generic flat plate PV	6.00	kW
Storage	Generic 1kWh Lead Acid	43	strings
Dispatch strategy	HOMER Load Following		

Schematic





Cost Summary



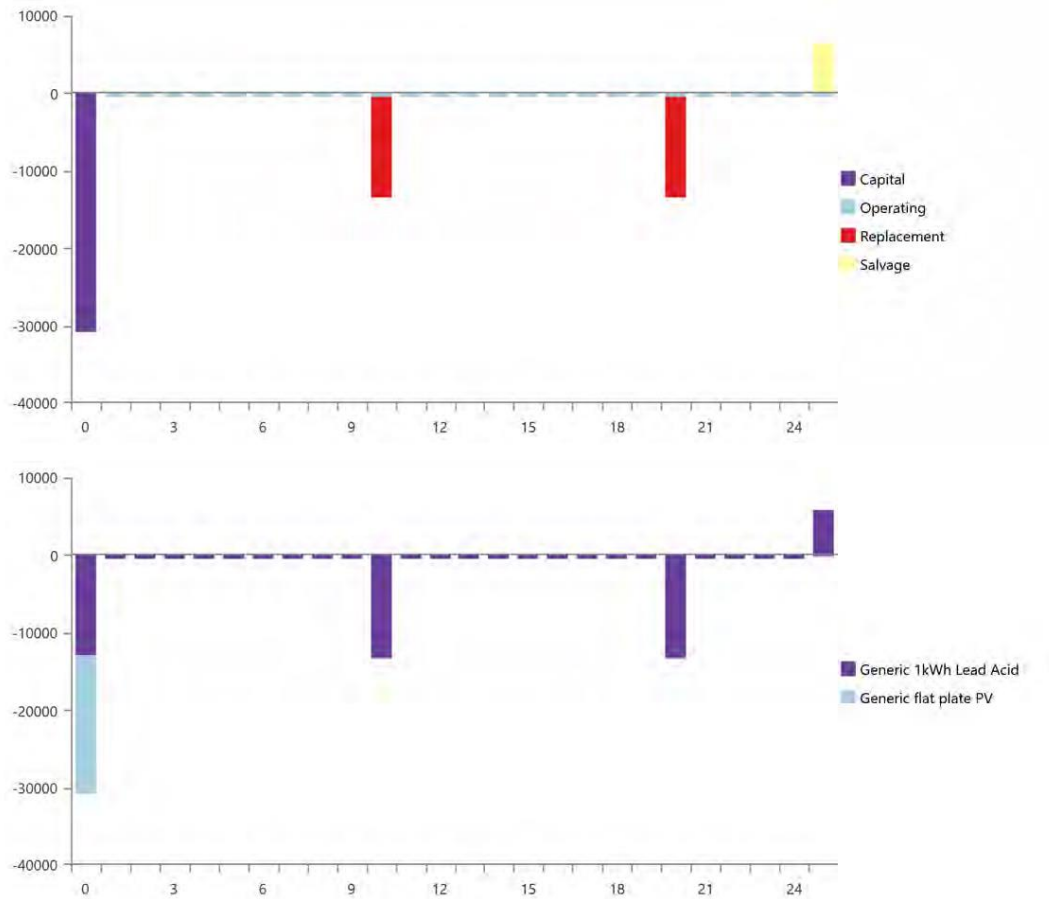
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Lead Acid	RM12,900	RM5,559	RM11,396	-RM1,545	RM0.00	RM28,310
Generic flat plate PV	RM18,000	RM775.65	RM0.00	RM0.00	RM0.00	RM18,776
System	RM30,900	RM6,334	RM11,396	-RM1,545	RM0.00	RM47,086

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Lead Acid	RM997.87	RM430.00	RM881.56	-RM119.52	RM0.00	RM2,190
Generic flat plate PV	RM1,392	RM60.00	RM0.00	RM0.00	RM0.00	RM1,452
System	RM2,390	RM490.00	RM881.56	-RM119.52	RM0.00	RM3,642

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	3,896	kWh/yr
Unmet Electric Load	2.87	kWh/yr
Capacity Shortage	3.69	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	8,638	100
Total	8,638	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	4,106	100
Deferrable Load	0	0
Total	4,106	100



PV: Generic flat plate PV

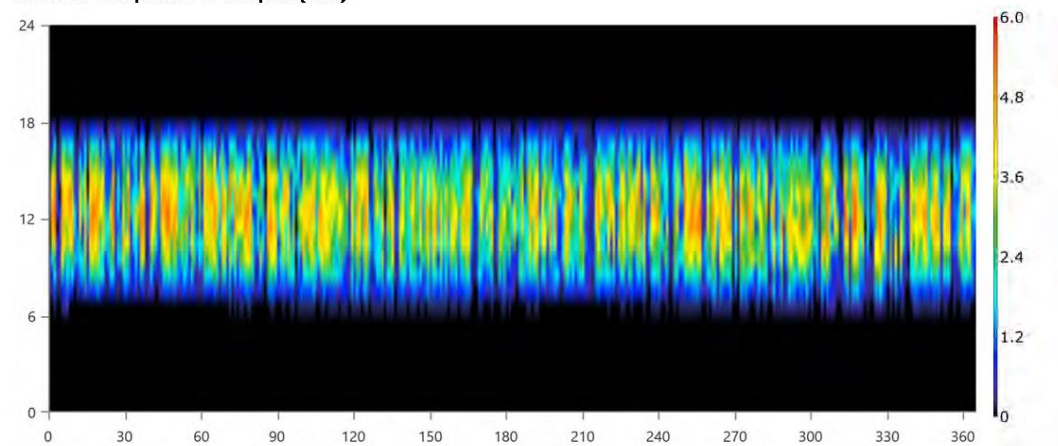
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	5.78	kW
PV Penetration	210	%
Hours of Operation	4,324	hrs/yr
Levelized Cost	0.168	RM/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	6.00	kW
Mean Output	0.986	kW
Mean Output	23.7	kWh/d
Capacity Factor	16.4	%
Total Production	8,638	kWh/yr

Generic flat plate PV Output (kW)





Storage: Generic 1kWh Lead Acid

Generic 1kWh Lead Acid Properties

Quantity	Value	Units
Batteries	43.0	qty.
String Size	1.00	batteries
Strings in Parallel	43.0	strings
Bus Voltage	12.0	V

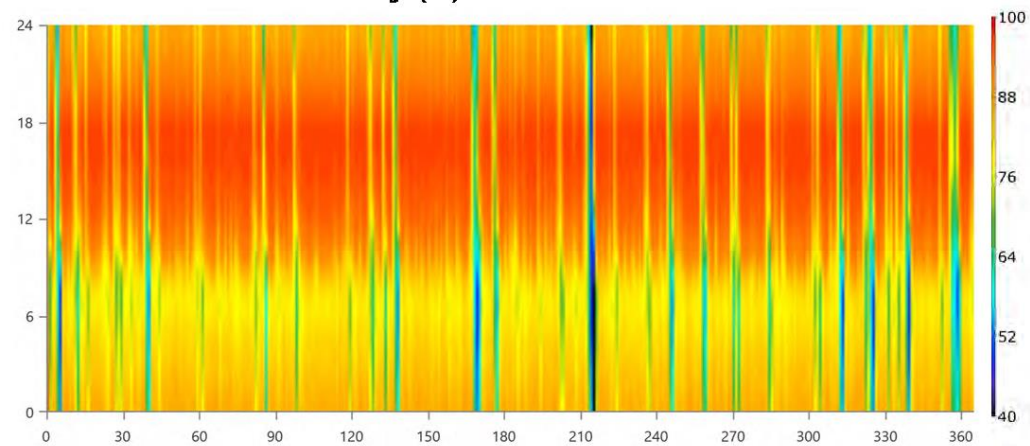
Generic 1kWh Lead Acid Result Data

Quantity	Value	Units
Average Energy Cost	0	RM/kWh
Energy In	3,212	kWh/yr
Energy Out	2,577	kWh/yr
Storage Depletion	7.63	kWh/yr
Losses	643	kWh/yr
Annual Throughput	2,881	kWh/yr

Generic 1kWh Lead Acid Statistics

Quantity	Value	Units
Autonomy	55.0	hr
Storage Wear Cost	0.419	RM/kWh
Nominal Capacity	43.0	kWh
Usable Nominal Capacity	25.8	kWh
Lifetime Throughput	28,808	kWh
Expected Life	10.0	yr

Generic 1kWh Lead Acid State of Charge (%)

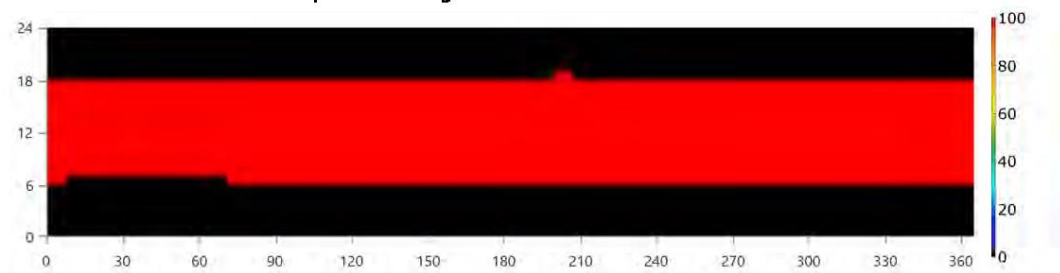




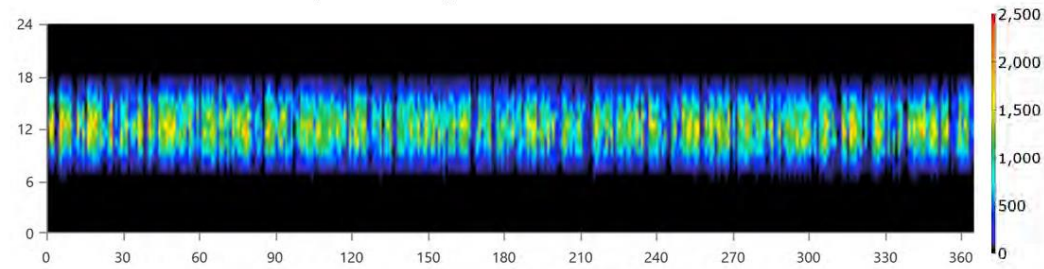
Renewable Summary

Capacity-based metrics		Value	Unit
Nominal renewable capacity divided by total nominal capacity		100	%
Usable renewable capacity divided by total capacity		100	%
Energy-based metrics		Value	Unit
Total renewable production divided by load		210	%
Total renewable production divided by generation		100	%
One minus total nonrenewable production divided by load		100	%
Peak values		Value	Unit
Renewable output divided by load (HOMER standard)		2,164	%
Renewable output divided by total generation		100	%
One minus nonrenewable output divided by total load		100	%

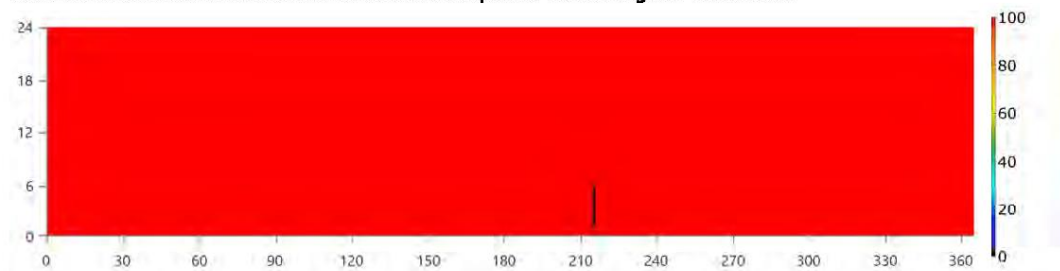
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load





Compare Economics

IRR (%):**N/A**

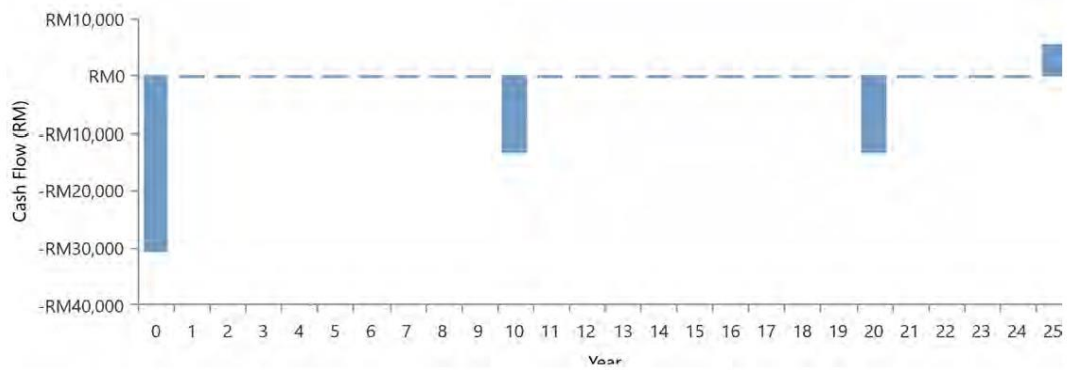
Discounted payback (yr):**N/A**

Simple payback (yr):**N/A**

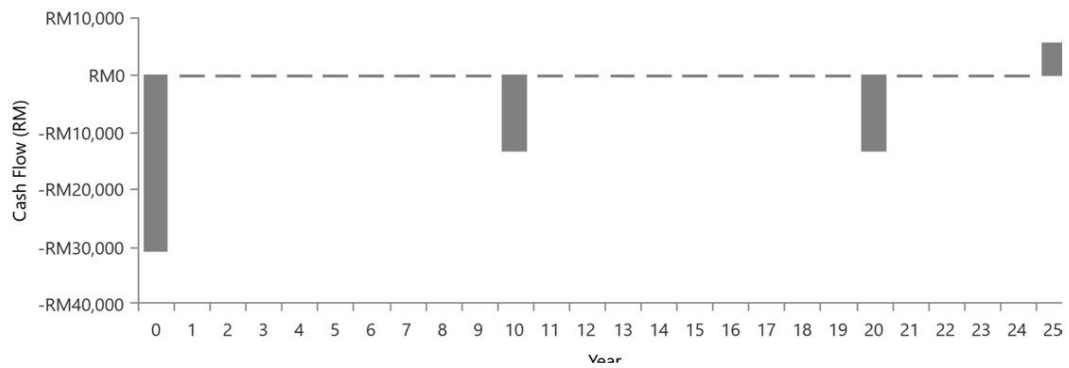
	Base System	Proposed System
Net Present Cost	RM47,086	RM47,086
CAPEX	RM30,900	RM30,900
OPEX	RM1,252	RM1,252
LCOE (per kWh)	RM0.887	RM0.887
CO2 Emitted (kg/yr)	0	0
Fuel Consumption (L/yr)	0	0



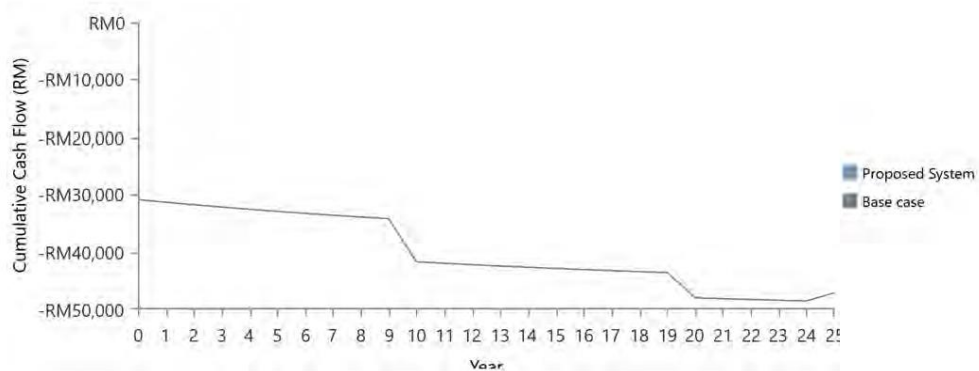
Proposed Annual Nominal Cash Flows



Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows





Time series charts:

