DEVELOP AN INTEGRATED MICRO-GRID CONTROL PLATFORM FOR RESILIENT AND SUSTAINABLE ENERGY MANAGEMENT IN DISTRIBUTION NETWORKS

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1. DECLARATION

I declare that this is my own work and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

31/08/2024

Signature: Date:

The above candidate has carried out research for the PhD/MPhil/Masters thesis/dissertation under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor:

Signature of the Supervisor: Date:

2. DEDICATION

I dedicate this detailed thesis for the future research endeavors in electrical engineering as a motivation. And I also dedicate this for the people who were with me and supported me in every second to go to the top.

3. ACKNOWLEDGEMENT

Completing this research was not easy as well as single-handed task. First, I need to thank Prof. K.T.M.U. Hemapala, Dean, Faculty of Engineering, who recruited me as a researcher for Smart Grid Research Group. His advice always drove me through this research journey and motivated me to work in the research and development field. Simultaneously, I want to thank Prof. Lidula N. Widanagama Arachchige and Dr. W.D. Prasad, who evaluated my research. Their advice, suggestions and comments were always valuable for me to shine up my research quality.

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Thank you

M.A.S. Wasitha

4. ABSTRACT

Microgrids are emerging throughout the world electrical engineering community as a feasible and more practical technical solution for renewable energy integration and small-scale harvesting. Microgrids are local area power networks that can be either connected or isolated from the grid. Microgrid controlling is a necessity in operation of microgrid due to the requirements of the grid stability, energy management as well as improving local controllability. The principle of this research is to develop microgrid controller, which follows resilient and sustainable energy management principles for a research level microgrid setup inside the UOM-LECO Smart Grid Research Lab. After a thorough literature review, a control platform with an energy management system was proposed which maximizes PV harvest and directs it to the customers. And the research contains simulated microgrid development with controls to implement its control strategies, using real-time digital simulator (RTDS) as a novel technological tool introduced to Sri Lanka. A new addition of hardware development is proposed to the lab to setup microgrid platform inside the lab environment to do further research in microgrid controlling. Simulation results were taken accordingly to claim the functioning of the control platform as well as the results are validated under the functioning of hardware platform.

Keywords: Microgrids, renewable energy, real-time digital simulators, sustainable energy management, resiliency

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8. LIST OF ABBREVIATIONS

Abbreviation	Description
DER	Distributed Energy Resources
PV	Photo Voltaic
DSO	Distribution System Operator
MPPT	Maximum Power Point Tracker
DC	Direct Current
AC	Alternating Current
PMSG	Permanent Magent Synchronous Generator
BESS	Batttery Energy Storage System
BMS	Battery Management System
MG	Microgrids
UOM	University of Moratuwa
LECO	Lanka Electricity Company
SGRL	Smart Grid Research Lab
RTDS	Real Time Digital Simulator
PCC	Point of Common Coupling
AI	Artificial Intelligence
GFI	Grid Forming Inverter
PLL	Phase Locked Loop
EMS	Energy Management System
ESS	Energy Storage System
FIS	Fuzzy Inference Systems
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
DR	Demand Response
SDN	Software Defined Networks
RTS	Real Time Simulations
AVM	Average Value Model
AH	Ampere Hours
IGBT	Insulated Gate Bipolar Transistors
MW	Mega Watts
SOC	State Of Charge
TCP/IP	Transmission Control Protocol/ Internet Protocol
SCADA	System Control And Data Acquisition

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1. CHAPTER 1: INTRODUCTION

1.1. Problem Identification

Microgrids have become a much popular tool in the world, to improve renewable energy integration to the distribution systems. As the world is heading towards a certain fossil fuel crisis in the near future, renewable energy resources are becoming more popular than ever in the energy markets. Simultaneously, the huge emission of CO_2 to the environment caused by fossil fuel combustion has accelerated to establish reinforcements to use renewable energy systems continuously. The establishment of renewable energy systems are bound together the high technological equipment and control strategies in order to harvest maximum available energy and in most of the cases, these renewables are operated independently, despite of subjecting to a common control strategy. As the next evolution of renewable energy integration, microgrid concept has emerged for the recent distribution systems, together with smart grid applications[1], [2], [3].

According to IEEE 2030.7 standard, definition for microgrid can be quoted as "A microgrid is a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid"[4]. A microgrid controller is a must in a microgrid to establish its controllability within the defined area. With the development of computational hardware and software interfacing techniques, microgrid controllers have become more user friendly and controllable systems throughout the world.

Due to the rapid decrease of fossil fuel resources and its environmental impact, nations are eager to enhance sustainability concepts as initiatives in each sector. Usage of renewable energy in electrical power generation and other energy applications can be termed as one of the biggest sustainability implementations in recent technological developments. To make energy consumption more sustainable, implementation of various microgrid controls is used. These special control actions are named as "Energy Management System" of the microgrid, which is a set of integrated commanding functions implemented in the network[5], [6].

Power system resilience is a key factor that replicates the reliability of the power supply for the consumers. In fact, resilience is the ability of the power system to maintain steady operational conditions throughout time. Whether the system undergoes adverse weather conditions, faults, power imbalances etc., the system should have the ability to maintain its operational conditions. Microgrids themselves provide the best available solution to improve the power system resiliency by isolating it from the major gird outages. Microgrid controller plays a major role in this scenario as well by acting as a commanding device for the DERs and loads to operate in a resilient way[7], [8].

The intention of this research is to tackle microgrid controller development scenario to introduce more sustainable and resilient microgrid operation.

1.2. Microgrids

A microgrid, by definition, is a small area power network, that can integrate small scale power generation sources and storage systems and loads. More precisely, as per the IEEE 2030.7 standard states, "A microgrid is a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid[4]". The most important aspects of microgrids are DERs, defined electrical boundary and controllability.

Microgrids can be differentiated depending on their application. Microgrids can be identified in industrial sector, universities, rural and regional areas, islands as well as in shipboard applications. In this thesis the focus is to provide controller platform related to residential microgrids, since it is highlighted in every aspect of this thesis.

1.3. Distributed Energy Resources (DERs)

Rather than operating larger centralized energy resources, microgrids prefer integrating small scale generation resources, since microgrids are operated in distribution levels. So, microgrids contain small scale generation resources which can be shared assets of the defined boundaries as well as private assets of the consumers. For an instance, there can be rooftop solar PV inverters in kilowatt scale, owned by households and industrial consumers in the area as well as there can be diesel generators that can be operated by the distribution system operator (DSO) in the microgrid area[9].

And DERs can be categorized as power injectors as well as power storages. Solar PV is one of the major renewable energy resources that only injects power to the grid. On contrary, energy storages like batteries can release or absorb power with respect to grid.

1.3.1. Power Generation Resources

1.3.1.1. Solar Photo Voltaic (Solar PV)

Solar PV has become backbone renewable resource in microgrids throughout the time. Due to its high availability, relatively simple energy conversion techniques have made solar PV more popular. Solar PV systems are highly popular in residential areas, where consumers can produce electricity using rooftop solar integrations. And also, larger industrial buildings also tend to generate some of their energy consumption mostly by rooftop solar and sometimes from ground mounted solar. In the design of solar PV in a microgrid area, the availability of sunlight is the most important meteorological measurement that should be considered. Simultaneously, rainfall data, wind distribution and humidity also measured to forecast effective solar generation by modern systems. And also, expected load demand, shading effects, integration technologies are some other characteristic aspects to follow solar PV design in microgrids[10], [11].

The conventional structure of a solar PV system is shown in following figure 1.

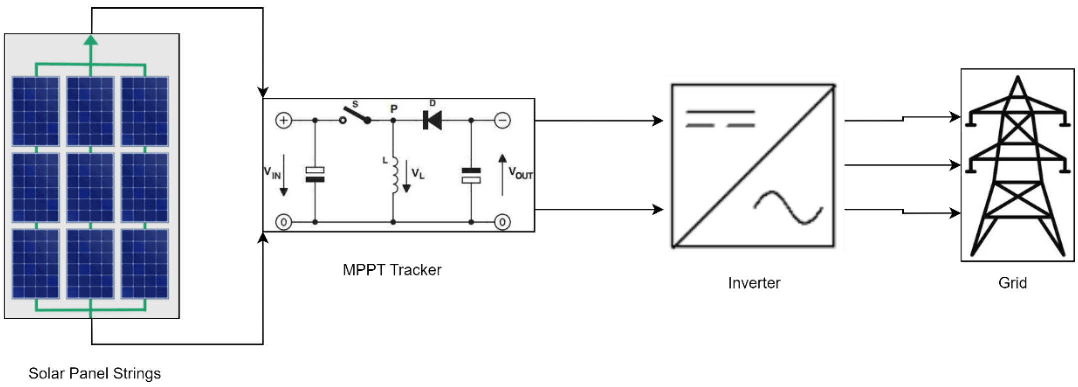


Figure 1: Solar PV system

Usually, solar panels are selected according to electrical power output intended to integrate with grid. An MPPT tracker is used to interface panel strings with the inverter to stabilize DC bus voltage input, which varies according to the sunlight. This buck-boost converter makes sure that the solar PV system extracts maximum power at its normal operation. Inverters are controlled normally using vector control methods as grid tie inverters and the load frequency controlling aspects are not assigned for solar inverters. In most of the cases, grid tie inverters are designed to stop operation at grid outages[10], [12], [13].

1.3.1.2. Wind Energy Generators

Usual wind turbines coupled with generators are aligned with horizontal axis, while smaller scale turbines are designed as vertically aligned. Design of wind power stations are mostly decided by the wind regime of the area, basically the estimation of the total power output is determined by the wind power distribution of the area. Coastal areas are much preferred for establishing wind farms and right now, advanced research are going on to feasibly establish off-shore wind farms[14].

In case of microgrids, wind energy integration is much challenging due to its high intermittency. Variation of wind speed and direction has been technically conquered by variable speed generators, power electronics, yaw control and pitch control techniques. However, standalone wind generators are not highly recommended in microgrids. Instead, combined systems with energy storage and energy management techniques are recommended with wind systems[13], [15].

In most modern cases, variable speed generators like induction generators are used to generate electricity at variable speeds, creating a variable frequency voltage. This voltage is then converted into DC and back to AC with fixed grid frequency for the injection. This is named as back-to-back converter fed generator. Similarly, doubly fed induction generators are also popular applications in industrial level wind generators.

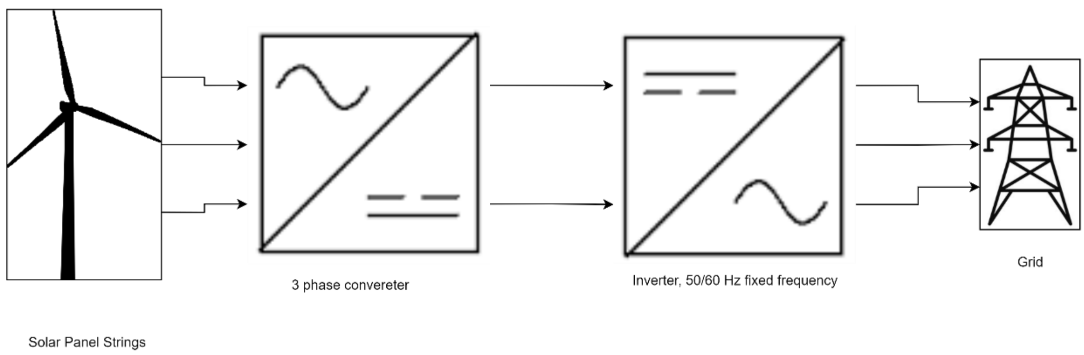


Figure 2: Wind generator with back-to-back power conversion

1.3.1.3. Small Hydro Power Plants

Apart from large hydroelectric power plants, microgrids prefer integration of mini and micro hydropower generators as DER. Small hydropower plants are much popular in rural areas which are rich in water. Without harming the eco diversity of the area, small hydro plants can be built as run of the river, dam integrated and pipe integrated turbines to be coupled with small scale generators. Most of the turbine types used are Kaplan turbines due to its ease of control with respect to water flaw availability. Impulse turbines are used in some cases with higher pressure heads. Permanent Magnet Synchronous Generators (PMSG) are popular in small hydro, due to its flexible operational constraints[16].

The integration of small hydro plants to the microgrid is more convenient than other renewables due to its operational stability and ease of forecasting. Small hydro power plants are well established in rural microgrids, stabilizing, and continuously operating throughout the day. These power plants can be chosen as base load power plants for the microgrid, with following specifically operating it at a common set point. To provide more stability, small hydro plants are integrated to the DC bus through power electronic converters. The typical structure of the small hydro power plant is shown in the following figure[17], [18].

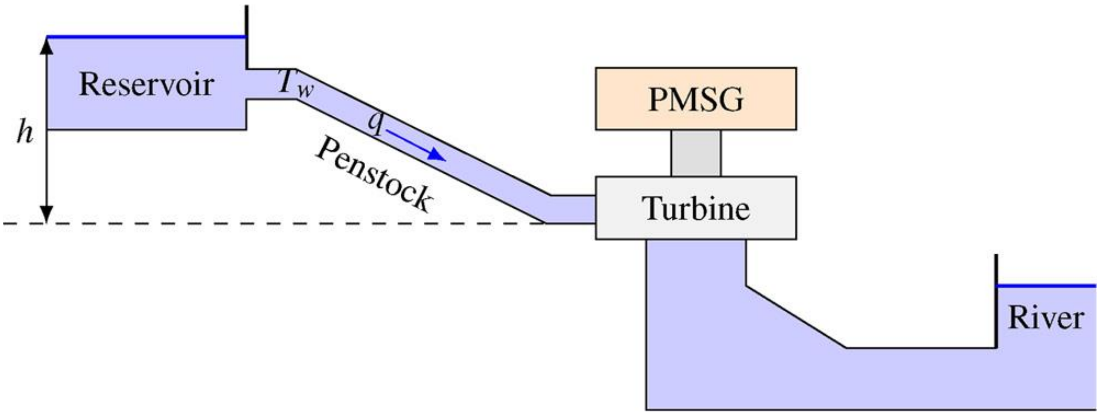


Figure 3: Structure of a small hydro power plant[16]

1.3.1.4. Other Renewables

Rather than conventional renewables, microgrids can contain sources like biomass powered generators, geothermal, fuel cell, tidal etc. Some of these technologies are still under development for commercial usage and specifically, biomass-based power resources are more common in industrial and rural microgrids[14].

1.3.2. Energy Storages

The requirement of energy resources emerges in microgrids due to several major reasons: intermittent nature of renewable energy resources and requirement of energy management.

1. Intermittent nature of renewable energy- Almost all the renewable resources act as highly variable conditions throughout the day. Especially, solar PV power can be varied with wind and cloud distribution and wind power can be varied with the time of the day. To manage sudden power drops or excesses, energy storage is required.
2. Requirement of energy management- renewable energy rich grids experience high power generations at low load levels and low power generation at high loading levels, which can be managed by energy storages. Apart from this scenario, most of the energy management scenarios are involved with energy storage.
3. Power quality maintenance- Reducing harmonics, frequency and voltage regulation, dc bus voltage regulation, pulsed load provision etc.

Grid level energy storage systems are operated as hybrid energy storages, which contains high power dense, low energy dense storages and high energy dense, low power dense storages combined[2], [11], [19], [20], [21]. Among most of the technologies, usage of battery energy storage is discussed under this section.

1.3.2.1. Battery Energy Storages

Battery Energy Storage Systems (BESS) are most common in microgrids while others are still under development. Battery storages are static elements, that results fast response in the system and capable of multitasking. As an example, a single grid tied BESS can perform frequency and voltage controlling, peak shaving, valley filling, load level management and so on. And also, in most cases of sustainable microgrids, BESS acts as the grid forming element in the islanded mode[22].

A battery storage contains the battery bank, DC-DC converter and 3 phase bidirectional converter. A separate controller block is usually integrated with the battery systems, which is termed as Battery Management System (BMS). This system incorporates primary level controlling aspects of the battery converters, which can be supervised by a high-level controller.

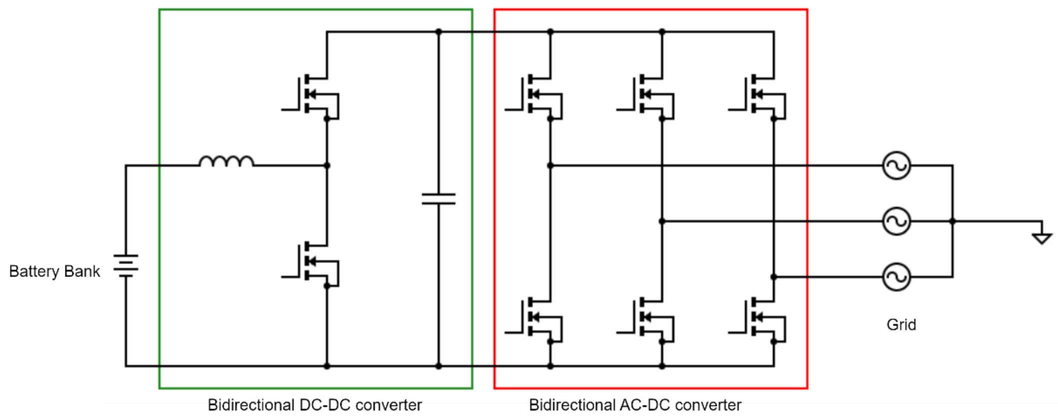


Figure 4:Power level components of a Grid-tied battery system

Most of the BESS are made of Li-Ion batteries due to their operational reliability, linear behavior of voltage vs capacity in a large capacity range which results in ease of controlling, longer lifespan, and other economic benefits[23].

1.3.2.2. Other Energy Storages

Apart from batteries, some other energy storage systems are also applied in grid level applications such as flywheels, pump storages, hydrogen fuel cells as well as super capacitors. These technologies are still emerging in microgrid applications due to high cost of development and technological difficulties.

1.4. Sustainable Energy Management

Sustainability concepts have become increasingly catching the attention in every sector due to limited resources, high consumption, and obviously environmental pollution. So, the power sector has become one of the major industries that follows sustainability concepts. Power sector technologies have adopted so far to minimize fossil fuel consumption and improve renewable penetration.

Sustainable energy management is a concept that adopts controlling techniques to maximize renewable penetration in the grid by using storages, forecasting methods and other optimization techniques. As an example, to serve the peak demand at the nighttime, solar PV generation can be stored at the daytime by allowing controller to optimally adjust power balance in the gird. In this scenario, the imported power from the utility can be minimized in the peak times. Some other research suggests that the scheduling of load and storages according to the forecasted solar generation profile to maximize renewable consumption, as mentioned in [6][5].

The intention of this research is to implement an energy management system, which follows sustainable concepts in the microgrid along with the controller.

1.5. Power System Resiliency

Operational resilience of the power system has become a major concern due to fast industrialization, growing population, and other various socio-economic concerns. MG concept itself is established in power sector as an improvement of power system resiliency. Simultaneously, the resiliency of the MG should be preserved in different perspectives. Maintaining system operational conditions steadfast as much as possible is the most important requirement of a resilient MG. Simultaneously, it is required to maintain a certain degree of redundancy in the system to manage operation in an equipment level failure[24], [25], [26]. And power system stability also plays a major role in system resiliency because instable grids can create power outages and power quality issues. This makes protection issues ought to be addressed in the resiliency problems.

A resilient microgrid should be capable of recovering from a disturbance scenario, as a part of its resiliency. The importance of advanced controlling requirements arises with the requirement of re-establishing the power grid. Automatic blackout start technologies should be adopted in microgrid controlling due to this reason. So, it is important to highlight that, microgrid control should be able to address resiliency improvement aspects of the grid as well[20], [27].

1.6. Microgrid Controllers

Handling microgrid operation throughout the time is not a simple task. Most importantly the power balance of the system must be maintained throughout the operation while its stability is kept resilient. And it should have the ability to address defined control strategies on resiliency and sustainability improvement techniques.

They should be a separate supervisory system that can handle the required control functions.

A microgrid controller is simply a hardware device that can handle controlling functions in the autonomous operation. Mainly it should have the capability to send control signals to DERs about operational conditions (commanding), calculating required operational conditions for each DER (computational capability) and creating operational workflows of controlling functions (scheduling). In most cases, microgrid controller acts as a central control device but due to high computational power requirements and less reliability, large scale central controllers are not preferred in commercial scale. In larger microgrids, distributed controllers are established to overcome above problems[3], [28], [29].

1.7. Scope and Objectives

The main objective of this research is to develop an integrated microgrid controller, that can implement resilient and sustainable energy management system inside a research level microgrid and implement the functionalities to manage the distribution network more efficiently within its operational conditions.

The specific objectives are,

- Develop a software-simulated microgrid controlling platform with relevant loads and source models.
- Integrating existing resources in the UOM-LECO Smart Grid Research Lab into controlling platform hardware, to demonstrate sustainable and resilient energy management techniques with the required accuracy.

The UoM-LECO Smart Grid Research Lab (SGRL) is equipped with 15kW solar inverters, 12kW battery inverters, programmable electronic loads that can be interconnected as a low voltage microgrid. The mentioned DERs should be connected to a controlling platform to achieve sustainable energy management in the network by maximizing renewable energy share and survive in islanded operation. And it is required to operate the microgrid in a resilient manner throughout the operation.

In this project scope, the hardware implementation of microgrid controller is proposed for the UoM-LECO Smart Grid Research Lab (SGRL). And also, as a novel addition for the electrical engineering research scope in Sri Lanka, this microgrid system and its controlling actions are simulated using Real-Time Digital Simulator (RTDS) as a more efficient and validated platform for electrical engineering.

1.8. Methodology

The project methodology is listed as follows.

1. Performing a literature review on microgrid controlling platforms and techniques of optimizing resiliency and integrating renewable energy sources with sustainable energy management.
2. Simulating a microgrid platform with collected data from the UoM-LECO research lab.
3. Developing a microgrid controller laboratory set up in the laboratory environment with controlling strategies.
4. Testing controller performance and validating with simulation results.

2. CHAPTER 2: LITERATURE REVIEW

2.1. Microgrid Structures

The aggregated microgrid can be structured in three major ways,

1. AC Microgrids (ACMG)
2. DC Microgrids (DCMG)
3. Hybrid Microgrids

2.1.1. AC Microgrids (ACMG)

To improve the distribution grid, ACMGs are well appropriate for the existing grid areas. In ACMGs, both sides of the Point of Common Coupling (PCC) are in AC electricity. In most cases, the ACMG is established in low voltage levels, where most of the residential DERs are generating utilization voltages (400/480V). In larger industrial microgrids, ACMGs are established in distribution voltage levels such as 11-33kV[30].

In ACMGs, DERs are connected to a common AC bus while most of the DERs are interfaced with the bus through DC/AC inverters. Hence it is mandatory to establish inverters for each DC source; battery, solar PV etc. And also, ACMGs are highly occupied with modular level AC generators such as diesel, steam-driven generators and most importantly mini hydro plants. Wind turbines are interfaced in conventional method to the distribution grid. Figure 5 shows a structure of a conventional ACMG[30], [31].

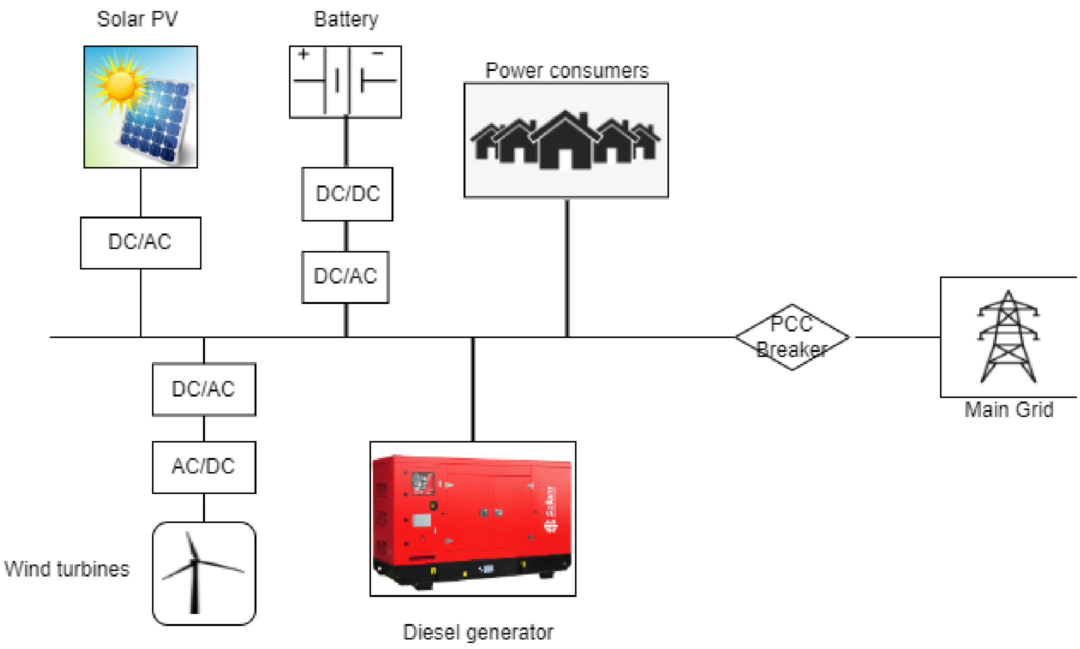


Figure 5: AC microgrid

2.1.2. DC Microgrids (DCMG)

Usually, DC microgrids are less common in practice due to most of the microgrid solutions are implemented as developments of existing AC distribution systems. DC microgrids show higher stability, higher efficiency, and controllability. But consumers who require AC electricity need to use inverters or must upgrade their equipment to be DC powered. Simultaneously, DC microgrids require larger Inter-Linking Converters (ILC) at the PCC to connect into the major AC grid. Diesel generators are less likely used in DCMG and usage of DC-DC converters is common at DER connections such as solar PV or battery[31], [32]. A schematic diagram for DCMG is shown below.

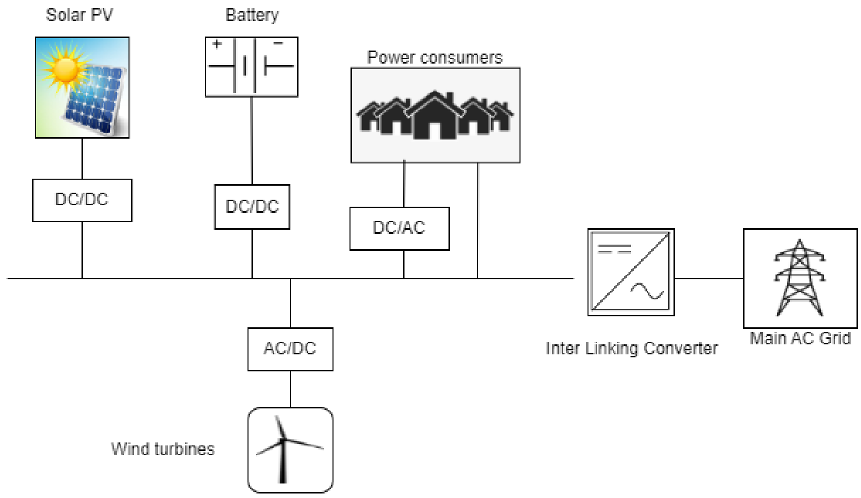


Figure 6: Structure of DCMG

2.1.3. Hybrid Microgrids

Hybrid microgrids contain AC busses as well as DC busses. DC buses are usually interlined with AC buses. The DC bus is preferred to connect renewables and DC loads while AC bus connects to diesel generators, loads and the grid. The existence of DC bus in a hybrid microgrid can more efficiently tackle the renewable intermittency problem since DC bus controls can be implemented in the controller. Hybrid microgrids are preferred in building industrial level microgrids since they prefer bulk renewable power generation. Reduced conversion stages improve the power quality, efficiency as well as the capital cost of the microgrid[29], [30], [33]. Figure 7 shows the structure of a hybrid microgrid.

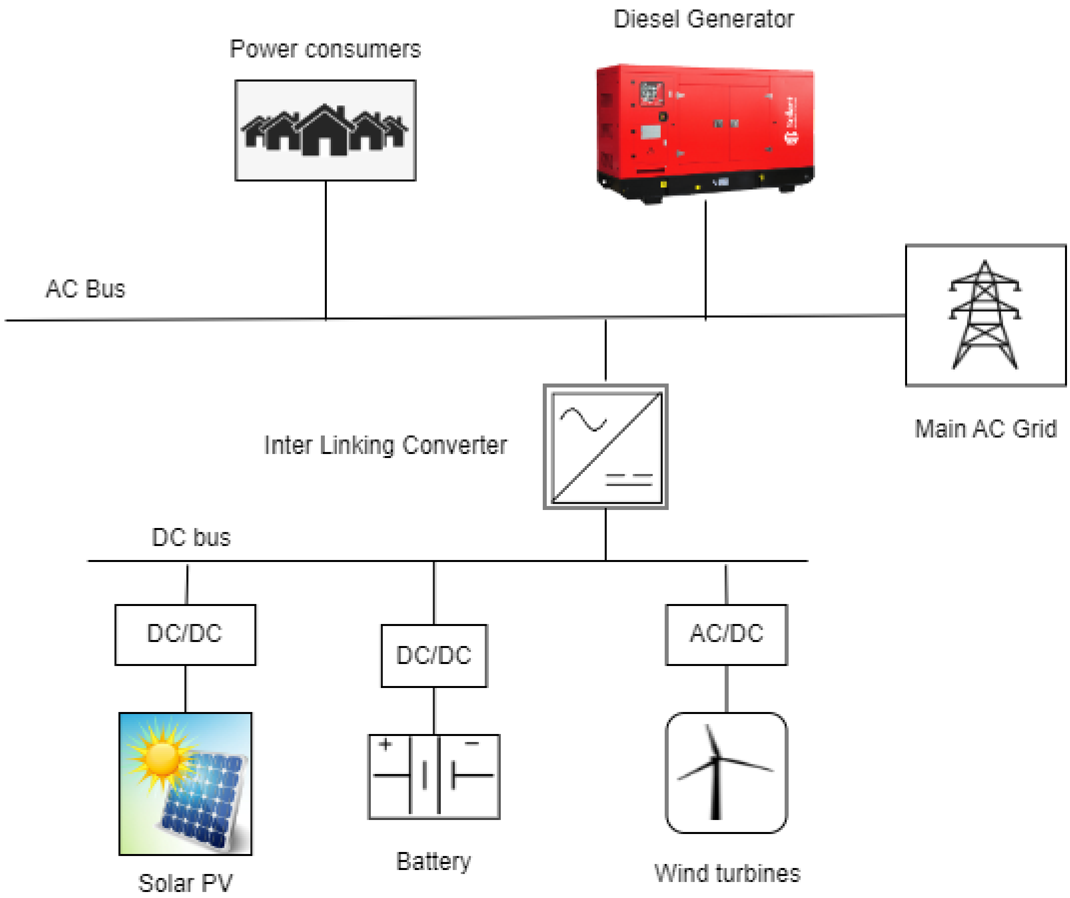


Figure 7: Structure of a hybrid MG

2.2. Microgrid Control Requirements

The requirement of microgrid control emerges in practice due to several reasons.

1. Autonomous operation- The operation of DERs should be done autonomously deciding its connection, disconnection, and power dispatch in a logical and accurate way. Considering the overall grid level, controls are required to change between operational modes; grid connected or islanded.
2. Economic operation- The microgrid should be able to operate in the defined economically beneficial way that lowers both energy and operational cost.
3. Improved sustainability- The sustainable operation of power distribution is highly promoted by world communities due to environmental pollution caused in power generation. Microgrid controllers can be used in improving sustainability of the system by maximizing renewable energy penetration.

4. Improved resiliency- Power system resiliency is an important fact for the consumers to experience a reliable operation. Microgrid controllers can provide controlling actions to maintain operational conditions of the microgrid steady.
5. Maintaining power quality- Power quality is also a key requirement in reliable power systems. Microgrid controllers should be able to handle system frequency and voltage in certain margins and reduce harmonics.
6. Energy management- The requirement of energy management emerges with the renewable intermittency and unavailability and as well as high loading levels. It is mandatory to release energy at high loading conditions as well as operate energy storages autonomously at high renewable penetrations.
7. System stability and protection- Microgrid controller is directly responsible for maintaining system stability by matching loads and generation sources correctly. And it should be able to coordinate protection functions at disturbance conditions inside or outside the grid[3], [29], [34].

2.3. Microgrid Controller Architectures

A microgrid controller is a system that can handle several predefined controlling functions autonomously by looking at the given inputs. Main functional capabilities of a microgrid controller are to command, compute, and schedule microgrid functions. This simply means that the microgrid controller acts as the brain of the microgrid. In most cases microgrid controller is a programmable controller integrated with communication interfaces and other required functions.

Microgrid controllers can be divided into three major architectures, centralized, decentralized and distributed.

2.3.1. Centralized Controllers

In this architecture, all the control functions are managed by a single control device. It is connected to all the DERs individually and can provide operational conditions for them. Central controllers should have the capability of taking required inputs (DER power outputs, power flow data, load variation etc.) and provide operational setpoints for all the DERs separately. Central controllers are usually integrated in small-scale microgrids with lower numbers of DERs. Major drawbacks of this architecture are the requirement of high computational power, lower reliability, and high risk of failure[28], [35], [36].

2.3.2. Decentralized Control

Microgrid controllers can be set up in several locations of a microgrid as multiple control agents which coordinates a certain part of DERs by each. This means that the microgrid contains several controllers distributed among. In decentralized control the communication among local controllers does not exist, which means that the distributed controllers act as independent controllers. Decentralized controllers contain control algorithms based on local variables which means that it receives information only form assigned DERs. Even though this architecture reduces the computational power of the controller and does not require sophisticated communication, this architecture can cause stability problems and coordination problems in at the operation due to the absence of information from other DERs[37], [38].

2.3.3. Distributed Controllers

To avoid technical difficulties in the above technologies, a distributed control structure is introduced. It can be identified as a development of the decentralized control structure by establishing communication platform in decentralized control agents. As an example, [39] suggests a distributed multi agent control platform based on consensus algorithm. And in layered control architecture, distributed control platforms are more efficient since certain control layers can be implemented in decentralized manner[35].

Figure 8 summarizes the controller architectures mentioned above.

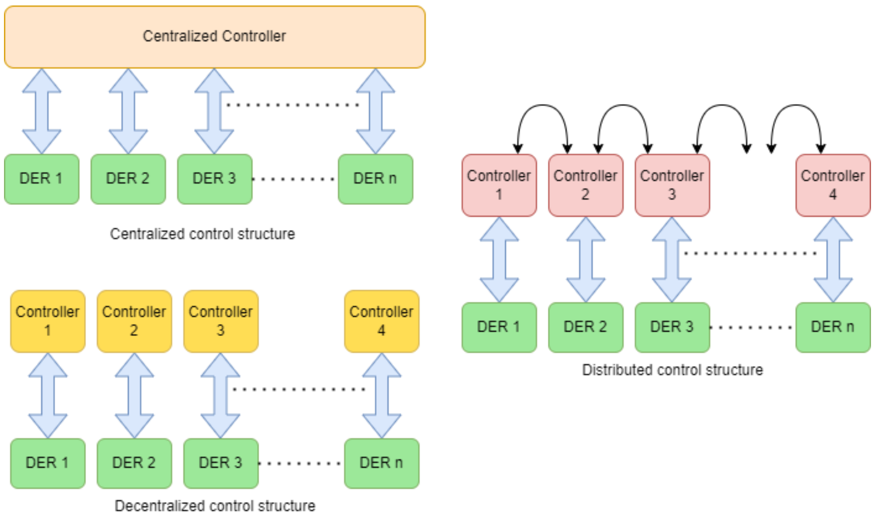


Figure 8: Microgrid Controller Architectures

2.4. Hierarchical Control Structure of Microgrids

In the development of modern microgrids, sophisticated control architectures are applied in both hardware and software sense. As mentioned above, controller architecture basically depends on the hardware design of the controller. Apart from this, the function integrated to the controller are also divided into three major categories, which creates a layered hierarchy in the control platform. A microgrid controller follows this structure is termed as hierarchical control structured platform[36].

In a hierarchical control structure, microgrid control functionalities are divided into two major control layers: primary, secondary, and tertiary. Each layer is assigned with some specific tasks to be fulfilled and upper control layer, which is named as supervisory layer is responsible for the mitigation and adjusting errors caused[30], [37].

2.4.1. Primary Control

Primary controlling can be identified as the lowest layer of control hierarchy, which is totally dependent on local information gathered. Primary controlling can be identified as the equipment level controlling since the control decisions are mainly dependent and relevant for the DER controlling. Due to its independency from the global grid variables, primary control layer is responsible for frequency and voltage stabilization, islanding detection, DER plug and play functionality, voltage and current set point adjustment is done by the primary control layer[37].

A well-known primary control function is the droop-based control in voltage and frequency. Droop-based control methods automatically adjusts the proportional power sharing between DERs, maintaining the system voltage and frequency levels optimally in the desired values. In implementation of energy management and intermittency of renewable energy, proportional power sharing will not be practical as always. To deal with this, separate primary controls should exist with energy storages to mitigate system frequency and voltages. Not only in the perspective of generation side, but primary controls are also added for demand side management strategies. As an example, load shedding option can be introduced [40].

2.4.2. Secondary Control

`Secondary control layer is mainly responsible for the supervised control of the primary layer. It means that the secondary control layer has functions to mitigate grid level frequency and voltage deviations caused by primary control loop. And the secondary layer is the main layer that implements most energy management functions in the grid level. It can contain optimization algorithms and sometimes AI based decision making algorithms that are useful in economic power dispatch, CO_2 minimization, or other energy management functions implemented in[37], [40].

Apart from energy management, the secondary layer is responsible for system level stability and protection functions implementation, blackout restoration, islanding and grid connection, power quality management etc. As a whole, secondary layer is the most important layer that coordinates DER into a single microgrid entity. Microgrid controller functional variations can be implemented time to time on this layer, so this layer is considered as the challenge in Microgrid control development. The major functional requirements of the secondary control layer is briefed in figure 9.

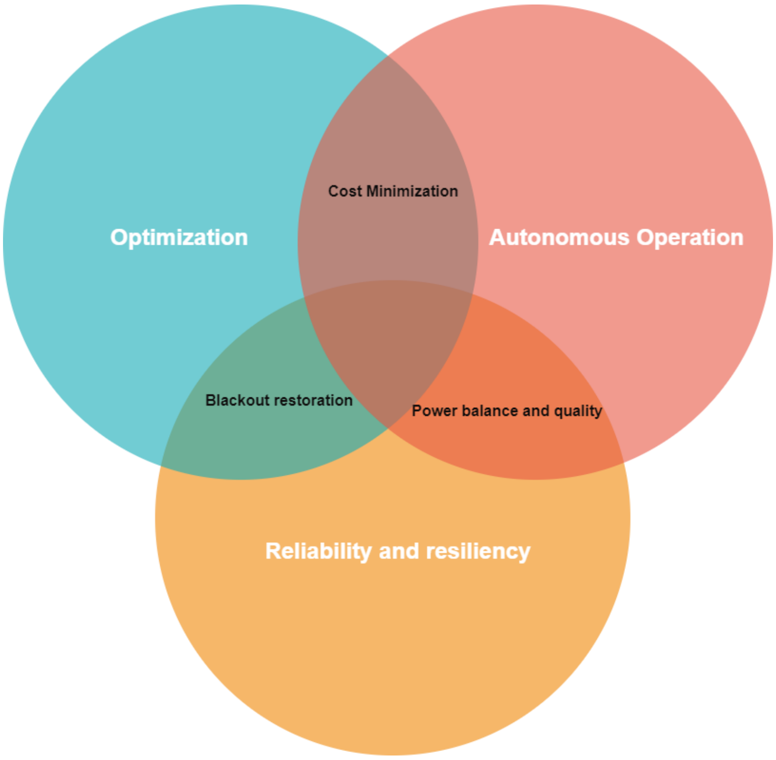


Figure 9: Functional requirements of the secondary control layer

According to [2], the secondary layer actions are briefly described below.

Cost Minimization-Secondary control actions related to cost minimization includes reducing operational, environmental and storage costs. Several research are done on considering various optimization techniques and cost aspects.

Blackout restoration- Operational sequence of blackout restoration is embedded in secondary control structure. This sequence contains protection and stability improvement techniques that avoids system going to a total blackout. The secondary control considers the load priority, level of battery power that can be safely released, availability of main grid and other DERs, in restoring the grid to ensure quick restoration.

Power balance and quality- To stabilize the disturbances occurred by renewable intermittency and pulsed load variations, energy storages are coordinated by the secondary layer functions. Simultaneously stabilizing frequency and voltage, mitigating harmonics are also in the scope of the secondary layer.

2.4.3. Tertiary Control

The tertiary control layer acts as the top layer of control architecture, supervising primary and secondary controls appropriately. The tertiary layer takes decisions related to utility grid level operational constraints. As an example, [2] suggests grid operator level controls for frequency deviations in the microgrid frequency and balance out power imbalances with grid level power exchange. Simultaneously, the tertiary controls are responsible for following grid level economic, environmental and whether constraints inside the microgrid operation. This suggests that the tertiary level is nothing but the Distribution System Operator (DSO) of the power grid and acts as a supervision control for the integrated microgrid.

In further sections under controlling functions, implementation of above control hierarchies is discussed. Figure 9 shows the hierarchical structure of the microgrid control as a summary.

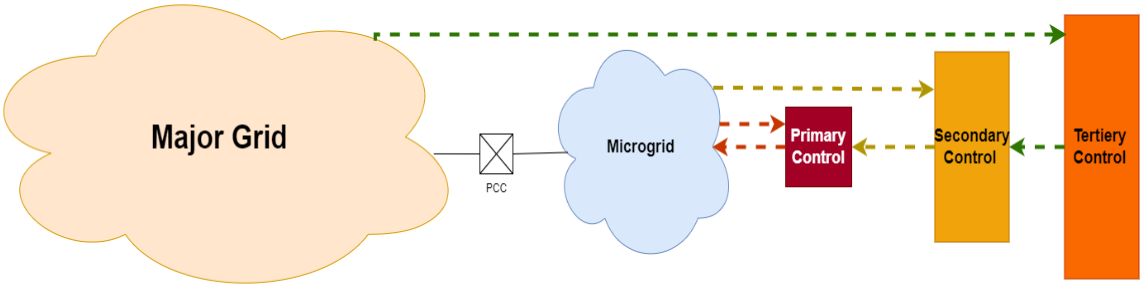


Figure 10: Control signal flow of hierarchical control structure

2.5. Microgrid Operational Modes

A conventional microgrid can mainly be operated in two major operational modes; grid connected and islanded [3].

2.5.1. Grid Connected Mode

A microgrid usually connected with the major utility grid at a PCC as described. When the major grid is in normal operation, the microgrid is mainly controlled under utility controls. It means that the frequency and the voltage of the grid is determined by the major grid controller settings. DER inside the microgrid adjusts their droop settings according to the grid values. Even though frequency and voltage is decided by the main grid, secondary controls inside the microgrid like cost optimization, economic dispatch, renewable energy maximization are handled by the microgrid secondary level controller. This mode is considered as most reliable mode of operation since a load can be served form various sources, including grid. As a major drawback, protection coordination of the microgrid can be challenging in grid connected mode since the inrush currents can be small at protection measurement level[34], [37], [41].

2.5.2. Islanded Mode

In case of main grid failure or limited access, islanded microgrids are formed by the microgrid controlling coordination. According to [42] [43], Microgrid islanding can be divided into two major types as follows.

1. Permanent islanded- These microgrids are usually established in rural areas or islands where a utility grid is not nearby.
2. Impermanent islanded- These microgrids are more common in practice, which have a connection between the main grids. This type of grid requires some additional control facilities to detect islanding, automatic disconnection and reconnection abilities.

An islanded microgrid requires a source that provides voltage and frequency references for the grid (i.e. a fixed voltage source), since the utility grid is no longer available. This requirement is called “grid forming control” in practice. In most of the cases, grid forming source is a diesel generator but in order to maintain sustainable goals of the grid, modern microgrids contain battery inverters which are capable of forming the grid. As an example, [44] suggests a method for modelling a grid forming inverter (GFI) with required controls. And also, [43], [45] suggests control structures of grid forming inverters, comparing with grid following ones. The structure of grid forming control is described in further chapters.

2.6. Microgrid Control Strategies

Microgrid control strategies are mainly the functional behaviors of the microgrid controller. Other than providing frequency or voltage controlling, control strategies are used for,

1. Providing optimal power dispatch of DERs.
2. Implementing energy management.
3. Power flow control inside the microgrid.
4. Fault protection and resiliency improvement.

And also, when focusing on primary control layer, DER control strategies, which are integrated inside them are also considered as control strategies for microgrids. For the convenience, control strategies are categorized and discussed under control layer architecture.

2.6.1. Primary Control Strategies

In the primary control layer, major focus on the control action to dispatch DER energy with required voltage and frequency. According to [46], the primary control strategies can be divided into two major categories, (i) droop-based control and (ii) Communication based control.

2.6.1.1. Droop-Based Control

Drop based controlling is operated without using communication infrastructure for power sharing. This is critical in connecting remote inverters, which causes high communication costs. Some of the common droop-based control strategies are described below. The droop control strategy is implemented by adopting synchronous generator droop control strategies under inverter control.

1. P/f and Q/V droops

   To understand this strategy, it is required to identify power flow between two voltage sources.

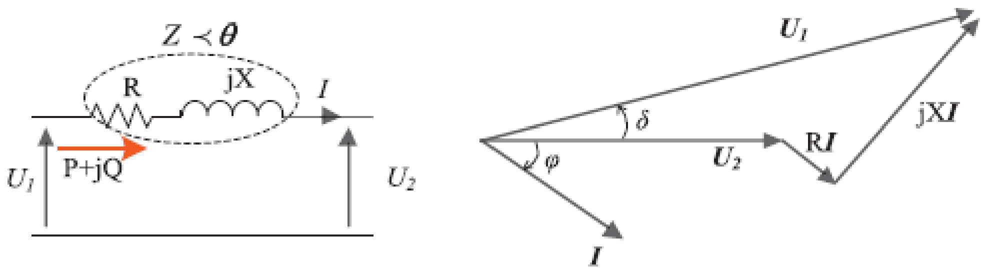


Figure 11: Power flow between two voltage sources

The active and reactive power flows can be calculated using first principles,

$$P = \frac{U_1^2}{Z} Cos\,\vartheta - \frac{U_1 U_2}{Z} \text{Cos}\,(\vartheta + \delta) \quad (1)$$

$$Q = \frac{U_1^2}{Z} Sin\,\vartheta - \frac{U_1 U_2}{Z} \text{Sin}\,(\vartheta + \delta) \quad (2)$$

Since the impedance Z=R+jX, by the substitution for Z and θ in 1,2 equations,

$$P = \frac{U_1}{R^2+X^2}[R(U_1 - U_2\,Cos\delta) + XU_2\,Sin\delta] \quad (3)$$

$$Q = \frac{U_1}{R^2+X^2}[-RU_2\,Sin\delta + X(U_1 - U_2\,Cos\delta)] \quad (4)$$

By 3 and 4,

$$U_2 Sin\delta = \frac{XP - RQ}{U_1} \quad (5)$$

$$U_1 - U_2\,Cos\delta = \frac{RP + XQ}{U_1} \quad (6)$$

Here, it is assumed that the R is negligible in power lines, compared to its X and the power angle δ is much smaller. From these assumptions,

$$\delta \cong \frac{XP}{U_1 U_2} \quad (7)$$

$$U_1 - U_2 \cong \frac{XQ}{U_1} \quad (8)$$

Above equations show that the active power flow between two voltage sources is proportional to the power angle between two sources, which is dependent on the system frequency. And also, reactive power flow is proportionate to the voltage difference between sources, which leads to the voltage controllability. The conventional droop scheme is presented as following equations.

$$\omega = \omega_{ref} - k_p P \quad (9)$$

$$V = V_{ref} - k_q Q \quad (10)$$

Here, k_p, k_q constants are termed as droop gains of the control. Usually droop gains are calculated as

$$k_p = \frac{\omega_{max} - \omega_{min}}{P_{max} - P_{min}} \quad (11)$$

$$k_q = \frac{V_{max} - V_{min}}{Q_{max} - Q_{min}} \quad (12)$$

The droop controlling characteristic graphs are shown in figure 10.

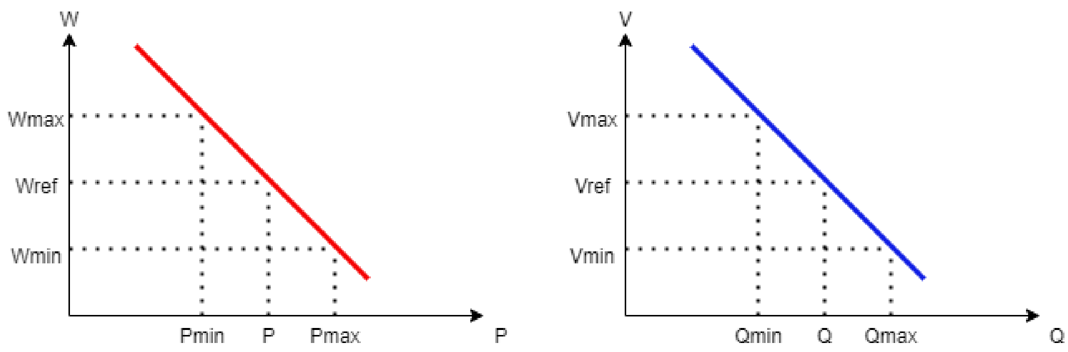


Figure 12: P/f and Q/V droop characteristics

Figure 13 shows the basic control scheme for inverter droop control.

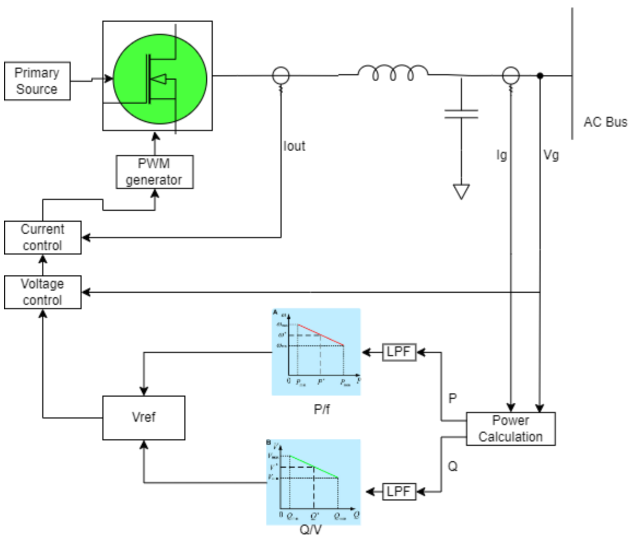


Figure 13: Inverter droop control scheme

2. Improved P/f-Q/v droop control methods

i. Addition of derivative terms- The rate of change of active and reactive power components is considered in the droop control to achieve stability in small load variations[47].

$$\omega = \omega_{ref} - k_p P - C_p' \frac{dP}{dt} \quad (13)$$

$$V = V_{ref} - k_q Q - C_q' \frac{dQ}{dt} \quad (14)$$

ii. Addition of impedance feedback loop- To achieve active and reactive power decoupling, harmonic level sharing as well as to eliminate circulating currents, this method is used. A new addition of virtual impedance feedback loop is done as follows[48].

$$V_{ref}^* = V_{ref} - Z_v(s) i_o \quad (15)$$

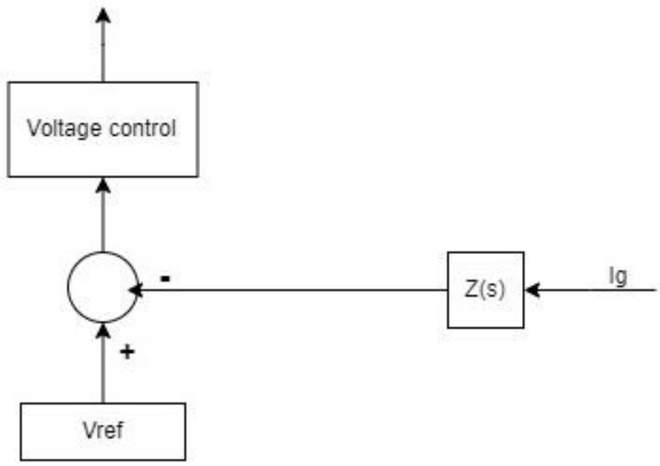


Figure 14: Virtual impedance loop

Other than these methods, novel microgrid controllers use P/V-Q/f droops, virtual frame transformation techniques are used in droop control.

2.6.1.2. Communication-based control

Communication based control techniques use more precise, controllable operation in DERs. They provide more accurate voltage and frequency outputs which leads to lower secondary layer controlling requirements. However, this controlling requires sophisticated communication infrastructure to handle operation[46].

1. Centralized control

This means that the primary controls contain inside a centralized control unit which measures the loading level and generates current set points and synchronized frequency to the inverter control units. For each DER, setpoint current is determined according to its capacity and this control method shares reference current into the desired ratio in both steady state and transient modes in the grid. The major problems involved in this control method is the difficulty to expand controlling number of units and the requirement of high precise communication[46]. Figure 15 shows a typical centralized primary controller architecture.

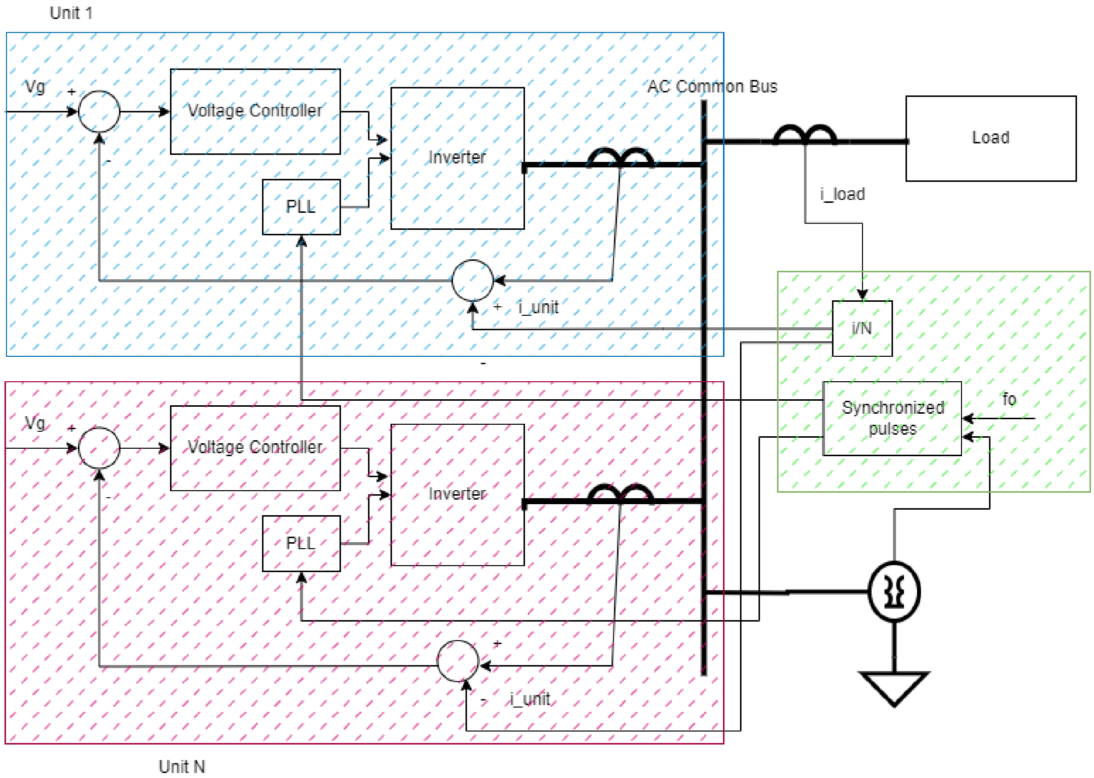


Figure 15: Centralized control

2. Decentralized control

   Unlike centralized controlling, this method contains individual controlling circuit for each DER to operate at desired average current set point, which is shared by a current sharing bus among parallel DERs. On of the key feature of this method is that the current regulator is used to mitigate the frequency output. The requirement of low bandwidth communication is also a pro in this technique. However, the interconnection between the DERs create lower degree of freedom to expand the system as well as redundancy of the system[46].

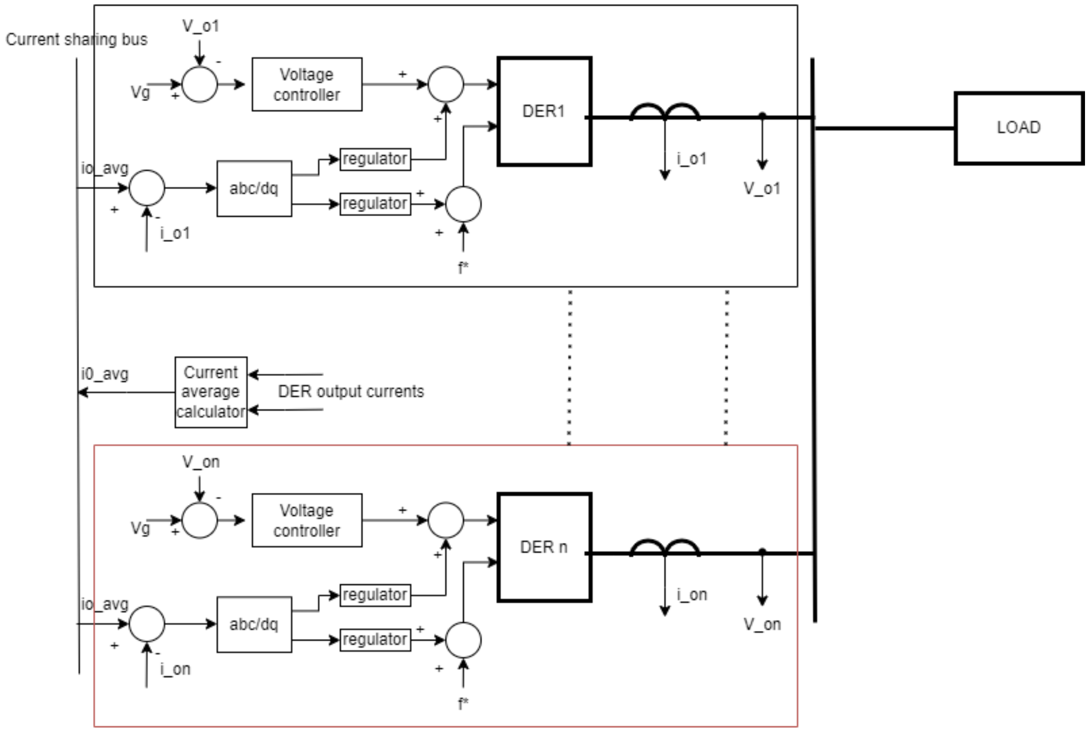


Figure 16: Distributed primary control

3. Master-slave control

   This controlling is adopted when one DER is operated as the master, which controls the voltage of the connected AC bus and determines the reference currents for each DER depending on its availability and dispatchability constraints. In this method, slave converters do not require PLL since they are synchronized with the master[46].

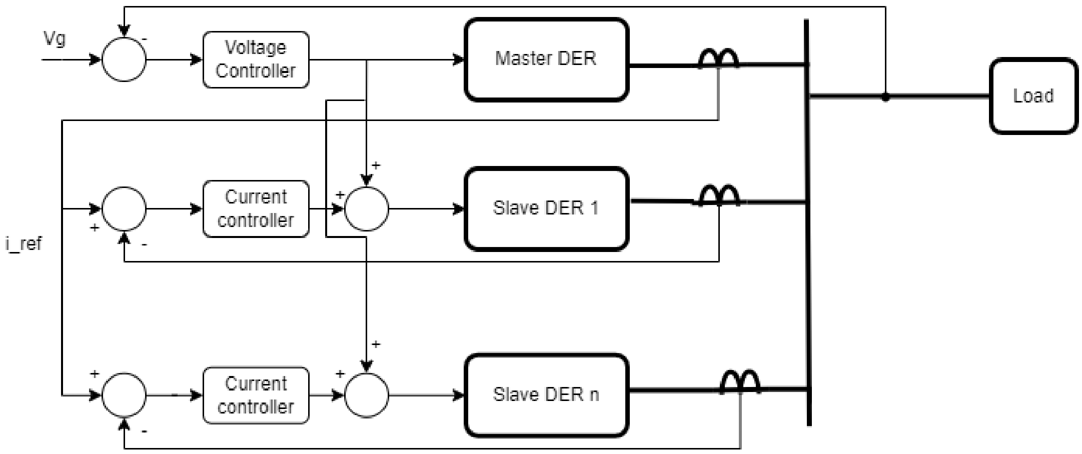


Figure 17: Master-slave control method

2.6.2. Secondary Control Strategies

Secondary layer controls mainly focus on adjusting frequency and voltage deviations caused by primary control layer and implementing microgrid level energy management strategies. In this control, the discussion on Energy Management System (EMS) is highly required since it directly relates to the operational management and engineering quality of operation inside the microgrid.

2.6.2.1. Energy Management System of a Microgrid

Based on the output power produced by distributed energy resources (DERs), device state, predicted load and weather, and fuel and electricity prices, an EMS ensures the economic activity and efficiency of a microgrid. The output power of DERs, ESSs, and energy exchanges can all be correlated and managed by an EMS. As a result, an EMS can be utilized to accomplish one or more goals, including balancing the energy in transmission lines, minimizing daily operating expenses, and monitoring power both proactively and reactively. In this scenario, an EMS is essential for MGs to function effectively, guarantee their dependability, and meet power balancing requirements over the long run [2]. Ultimately, the sustainability of the microgrid is represented by the operation of the EMS.

In any EMS, optimization has become a higher priority. To look about the requirement of optimization, various researchers have followed different perspectives. And the optimization algorithm for the system also differs depending on the number of variables, computational time as well as the operational reliability of the algorithms.

Some of the literature-based EMS functions are summarized in Table 1.

Table 1: EMS algorithms

Ref	Optimization approach	Contributions to the topic	Limitations	Controller Architecture	Uncertainty handling approach
[49]	Model Predictive control	Two stage EMS with economic scheduling and uncertainty rectification through forecasting	Computational power requirements are not discussed. No evaluation of emission costs	Centralized	Forecasting

[50]	Stochastic optimization	Expected value of operational cost is minimized during islanded periods.	Computational time and hardware requirement is not assessed. Demand response is not considered	Centralized	Monte Carlo simulation and backward reduction methods
[51]	Matrix real coded genetic algorithm	Marginal price bids for each DER in MG are considered to minimize the operational cost	Emission costs not considered. Demand response scenarios not considered.	Centralized	Neural networks
[52]	Fuzzy Logic	Fuzzy-based EMS is proposed for MG generation scheduling and battery level management.	High computational cost. Does not consider losses.	Centralized	Forecasting
[53]	Particle Swarm Optimization	Operational and reliability constraints were assessed. Solar power uncertainty was modelled using point estimators.	Cause fast battery degradation. Lack of system loss modelling	Centralized	Point estimators
[54]	Rule-based approach	Hybrid MG. Power balancing in building integrated MGs. Stabilization of DC bus voltage	Cost level optimization is minimum (Operational cost, energy transaction costs are not added) Demand response strategy not included	Centralized	Forecasted
[55]	Dynamic programming	Cost components: operational cost, penalty cost for load shedding,	Fast degradation of battery	Centralized	Forecasted

In implementation of EMS, the system interpretation can be done in two major methods; rule-based and artificial intelligence (AI) based. Rule based EMS contain simple algorithms with defined set of rules and logics. On contrary, AI based EMS operates with help of neural networks to adjust conditions according to a reference dataset. Rule based EMS are more flexible in operation and consumes lesser computational power.

As an example, [53] contains a rule based operational algorithm, empowered by robust optimization technique in modelling the load and demand uncertainty. The objective function of the EMS is to minimize operational cost and the pollution cost of the microgrid. The optimum solution is found by the Particle Swarm Optimization technique, by considering hourly values for selling and purchasing energy costs, DG operational and pollution costs, battery operational cost, solar and wind power parameters as required.

Similarly, [56] contains a rule-based algorithm integrated and grid-independent microgrid system which uses grasshopper optimization algorithm under three main objective functions. Three main objective functions are of great importance in the design of microgrid, namely, the economic aspect objective (cost), the technical aspect objective (reliability), and the environmental aspect objective (CO_2 reduction). And also [57] discusses a rule-based EMS system empowered by fuzzy inferential system (FIS). The optimization procedure aims to maximize the overall profit gained by the energy trading with the primary grid, which includes the BESS degradation cost. Furthermore, the FIS-EMS does not consider any contract constraint for the energy trade between the microgrid and the grid. Mixed Integer Linear Programming (MILP) is another optimization technique used in [58], which uses Model Predictive Control (MPC) technique to optimally control cost effective power sharing among the DERs. Additionally, this control structure uses an architecture, which fuses primary and secondary control layers into a single controller by defining two controller operation times, representing primary and secondary control layers. The “fast" model is used for predictions that are close to the current sampling time, while the “slow" one is used for predictions that are farther away in time.

Table 2 describes some of the objective functions described in literature.

Table 2: Objective functions used in EMS.

Reference	Objective	Equation	Description
[59]	Grid Cost	$\sum_{t=1}^{T} P_{grid,t} * C_{grid,t}$	$P_{grid,t}$: $Grid\ exchange\ power\ at\ time\ t$ $P_{grid,t} = P_{load,t} - P_{pv} - P_{BESS}$ $C_{grid,t} = Cost\ of\ power\ consumption\ at\ time\ t$
[60]	Total operational cost	$\sum_{t=1}^{T}\sum_{i}[F(P_g(i,t))\ I(i,t) + SU(i,t) + SD(i,t)]$	$P_g = Thermal\ unit\ dispatch\ at\ time\ t$ $I = PV\ terminal\ current$ $SU = Start\ up\ cost$ $SD = Shut\ down\ cost$

[61]	Total operational cost	$[\sum_{t=1}^{T}\sum_i E_g^d(i,t) * C(i_d,t)] + [\sum_{t=1}^{T}\sum_i E_g^{nd}(i,t) * C(i_{nd},t)]$	$E_g^d = Energy\ delivered\ from\ dispatchable\ loads$ $E_g^{ind} = energy\ delivered\ form\ non - dispatchable\ loads$ $C(i_d,t), C(i_{nd},t) = Unitary\ cost\ of\ energy\ for\ dispatchable\ and\ non\ dispatchable\ loads$
[62]	Production cost	$\sum_{t=1}^{T}\left(C_t^g + C_t^{g'} + C_t^{ESS+} + C_t^l + C_t^{ESS-} + \Omega_t\right) * \Delta t$	$C_t^g + C_t^{g'} = cost\ of\ energy\ for\ dispatchable\ and\ non - dispatchable\ loads$ $C_t^{ESS+}, C_t^{ESS-} = Cost\ of\ energy\ for\ charging\ and\ discharging\ the\ BESS$ $C_t^l = cost\ of\ power\ for\ responsive\ load\ demand$ $\Omega_t = Penalty\ cost$
[63]	Power loss	$P_{loss} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{i0} P_i + B_{00}$	$B_{ij}, B_{i0}, B_{00} = B - matrix\ coefficients$ $P_i = power\ by\ each\ unit$
[64]	Charging cost	$\sum_{t=1}^{T} M(t) * P(t)\Delta t$	$M(t) = Unit\ price\ at\ time\ t$ $P(t) = Charging\ power\ at\ time\ t$
[65]	Purchase cost	$\sum_{t=1}^{T}(C_{pur}(t)P_{pur}(t)T_s - C_{sold}(t)P_{sold}(t)T_s)$	$C_{pur}, C_{sold} = Purchasing\ and\ selling\ costs\ at\ time\ t$ $P_{pur}, P_{sell} = power\ purchase\ or\ sold\ at\ time\ t$
[65]	Shortage cost	$\sum_{t=1}^{T} \rho_{st,t} * g_{st,t}$	$\rho_{st,t} = Penalty\ cost\ of\ shortage$ $g_{st,t} = Shortage\ of\ energy$
[66]	Load shedding cost	$\sum_{t=1}^{N_D} C_{Di} * \Delta P_{Di}$	$C_{Di} = cost\ coefficient\ of\ i\ th\ load$ $\Delta P_{Di} = active\ power\ shedding\ of\ i\ th\ load$

The energy management system of a microgrid can operate, targeting one or more objectives as defined in table 2. The more objectives you target, the more computational power required and the higher the controller operation time required. The upcoming sections discusses how to direct these objective functions to improve sustainability and the resiliency of the microgrid to the expected degree.

2.6.2.2. Sustainable Energy Management of a Microgrid

Sustainability of energy is defined as the generation, transmission as well as distribution of energy with minimizing environmental disturbance, pollution as well as resource wastage as explained earlier. The operation of EMS can be dedicated to improving the sustainability of the microgrid operation by introducing conceptual basis of sustainability through various objective functions.

As an example, [5] describes an energy management system with two main objective functions.

- The equivalent CO2 emission from a DG unit operating at a given loading level is considered and taken into the optimization model as total emission cost of CO2.

$$J_{em} = \gamma \sum_{g,k}[\left(a_g^{em} P_{g,k}^2 \Delta t_k + b_g^{em} P_{g,k} + c_g^{em} W_{g,k}\right)\Delta t_k + C_{g,k}^{em-sup} U_{g,k} + C_{g,k}^{em-sdwn} S_{g,k}]$$

(16)

Here, a, b, c are constants that represents emission level of the distributed generator at P loading level, $C_{g,k}^{em-sup}$ and $C_{g,k}^{em-sdwn}$ represents CO_2 emission levels at start up and shut down.

- Demand-shifting load models are integrated into the control to examine the possible impact of DR on the total system emissions and costs. Forecast load and renewable generation models are used in unit commitment modelling, forecast load and renewable generation models are used in DER scheduling and hence the operation of energy storage is managed to attain lowered CO2 emission as well. And the shiftability of loads subjected to demand response (DR) is also considered in unit commitment problem.

$$Supply = Demand$$

$$\sum_g P_{g,k} W_{g,k} + \sum_i \left(PV_{i,k} + PW_{i,k}\right) + \sum_n (P_{n,k}^{dch} - P_{n,k}^{ch}) = \sum_j (PD_{j,k}^c + PD_{j,k}^r + PD_k^{rs}) \quad (17)$$

In demand side, $P_{g,k}$ represents the power dispatch of fossil fuel-based generators and $PV_{i,k} + PW_{i,k}$ represents combined PV and wind power generation at time interval k. $P_{n,k}^{dch} - P_{n,k}^{ch}$ represents total power output of the battery banks. At the demand side, proportion of commercial and residential loads are considered as fixed load proportion for the system. PD_k^{rs} represents responsive proportion of the load which is shiftable.

Alternatively, [67] describes an EMS with an objective function of cost minimization, subjected to following constraints. Its sustainability is mainly ensured using emission constraints and storage constraints.

- Power balance

  $$\sum_{l=1}^{ul} P_l(t) - \sum_{i=1}^{ug} P_{DERi}(t) - \sum_{j=1}^{us} P_{ESSj}(t) - P_{gr}(t) + P_{gs}(t) = 0 \quad (18)$$

- Emission constraints- minimizing total emission of CO2, NOx and Sox emission of each DER is kept minimum levels.

  $$E_{CO2_{DERi}}(t)P_{DERi}(t) \text{ or } E_{CO2_{ESSj}}(t)P_{ESSj}(t) \text{ or } E_{CO2_g}(t)P_g(t) \leq E_{CO2}^{max} \quad (19)$$

  Similar constraints are developed for NOx and SOx.

- Dispatch constraints- Containing dispatch of each DER and ESS in between minimum and maximum levels.

  $$P_{DERi}^{min} \leq P_{DERi} \leq P_{DERi}^{max} \quad (20)$$

  $$P_{ESSj}^{min} \leq P_{ESSj} \leq P_{ESSj}^{max} \quad (21)$$

- Storage Constraints- Battery storages are operated to follow the equation below.

  $$W_{ESS}(t) = W_{ESS}(t-1) + P_{ch}(\Delta t)\eta_{ch} - \frac{P_{disch}}{\eta_{disch}}(\Delta t) \quad (22)$$

  $W_{ESS}(t)$ is the energy stored at time t and $W_{ESS}(t-1)$ is the energy stored at time t-1. η_{disch} ,η_{ch} are discharging and charging efficiencies respectively.

Similarly, [68] describes a centralized EMS for isolated microgrids, which is operated in cost minimization objective function while constraints avoid simultaneously turn on and off each distributed generation. And as a novel improvement, the power output of each distributed generator is kept under its maximum capacity to handle sudden load-generation imbalance, following the concept “spinning reserve”. The mathematical formulation of this is shown as follows.

$$\sum_{gd} \omega_{gd}[P_{gd}^{max} - P_{gd}] = R_{sv} \sum_g P_g \quad (23)$$

The variable R_{sv} is the ramp-up rate defined for generation.

Likewise, improving sustainability of the grid is nothing but the operation of EMS to handle microgrid operation in predefined sustainability constraints and an objective function.

2.6.2.3. Microgrid Resilience

As discussed in introduction, resilience of the microgrid is defined as its ability to sustain operational conditions at any time. Altogether, secondary control is solely responsible for handling resilient operation inside the microgrid.

Microgrid resilience can be divided into several categories as follows.

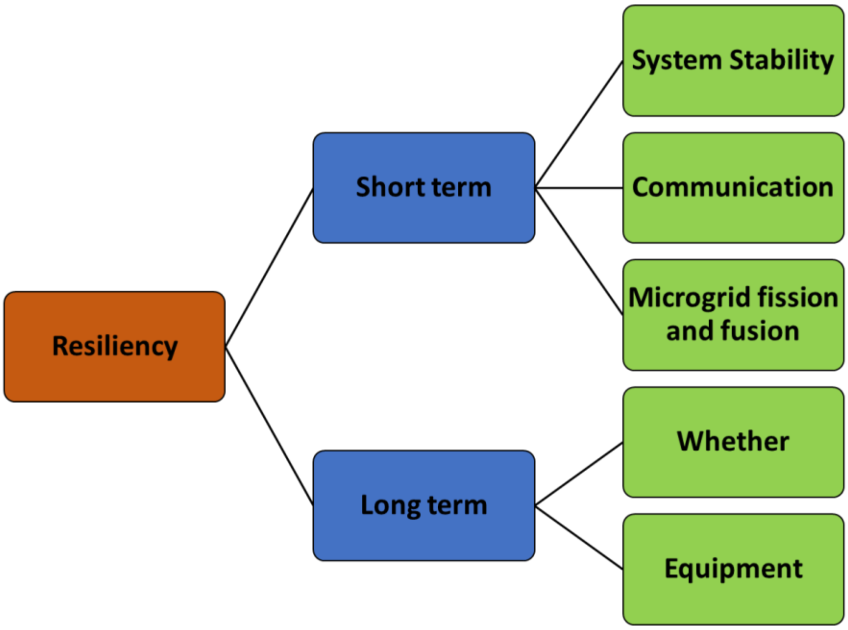


Figure 18: Microgrid Resiliency Categorization

1. Short-term Resilience

In terms of short-term resilience, system stability and protection play a key role. As an example, [19], [69]suggests usage of energy storages to optimize resilient operation of the microgrid. Especially, [19] discusses about possible short term as well as long term applications of energy storages to stabilize the grid, which is rich with renewable energy systems. The usage of energy storage systems to mitigate power fluctuations throughout time is well established in sustainable energy grids because these grids does not contain diesel or other fossil fuel generators in continuous operation. Similarly, [69] explains a development of a DER schedule with energy storages, specifically for resilience improvement. This controller integrated scheduling mechanism ensures minimum ESS level throughout the time horizon as a backup for the grid. And the research is done on two major resilience-oriented criteria (i) supplying energy to the maximum number of loads in the case of grid blackouts during an established period (Survivability criterion), and (ii) ensuring that critical loads can be fed during a complete day (Criticality criterion). The proposed methodology includes a formulation with which to carry out load and generation curtailment processes when the microgrid works in islanded mode.

Especially, protection enhancement is highly research throughout the academia to isolate faulty sections immediately, to control high inrush current flows inside grid as well as hold the grid until the backup power comes into the action at islanding. [43] suggests an adaptive protection scheme based on operational modes of the microgrid. The controller is given five major operational modes for the grid and protection schemes are defined based on each mode. Usage of machine learning and multi agent approaches in microgrid protection is discussed in [70]. In this design, they have used simulated fault cases of each node at different conditions and have prepared a combined dataset for fault currents. This dataset is then used to train a neural network to detect abnormality detection of the grid.

When it comes to ensuring grid operation, continuous operation of communication network is also required. Since most of the novel microgrid controlling methods depend on communication, high bandwidth wireless communication technologies are highly appreciated in microgrid sector. Other than the maturity of the technology, communication resilience requires certain degree of redundancy as well as security[71], [72]. As an example, [73] presents a cyber-resilient communication architecture for a campus microgrid, high-security data transfers and self-healing method to enhance resiliency. In self-healing criteria, the software-based network redefines communication nodes and restructures the network at a diagnosed network failure. To enhance security, it uses real-time network verification methods. The following figure describes the proposed system architecture.

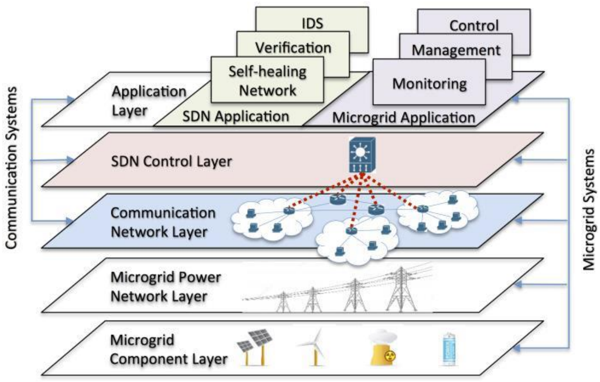


Figure 19: SDN enabled microgrid layered architecture[73].

On top of these scenarios, recent developments of microgrid controlling comprises dynamic partitioning of the sections at faulty situations. This control technique can be termed “microgrid fission” in this context. On the other hand, to ensure power supply continuum, several microgrids which are geographically distant can be integrated into a single system, in a major grid failure. It is safe to term this method as “microgrid fusion”.

As per [25], dynamic partitioning of DC microgrids is discussed depending on the load and generation disturbances as well as faulty conditions. DC microgrids are comparatively easy to partition because they do not require grid forming as well as need lesser power electronic interfaces and controls. Application of dynamic partitioning for AC microgrids require grid-forming inverters to maintain operational droop settings after successive islanding. So, it is basically novel battery inverters with grid forming control are recommended to be used in this scenario. The proposed system in the paper is shown below.

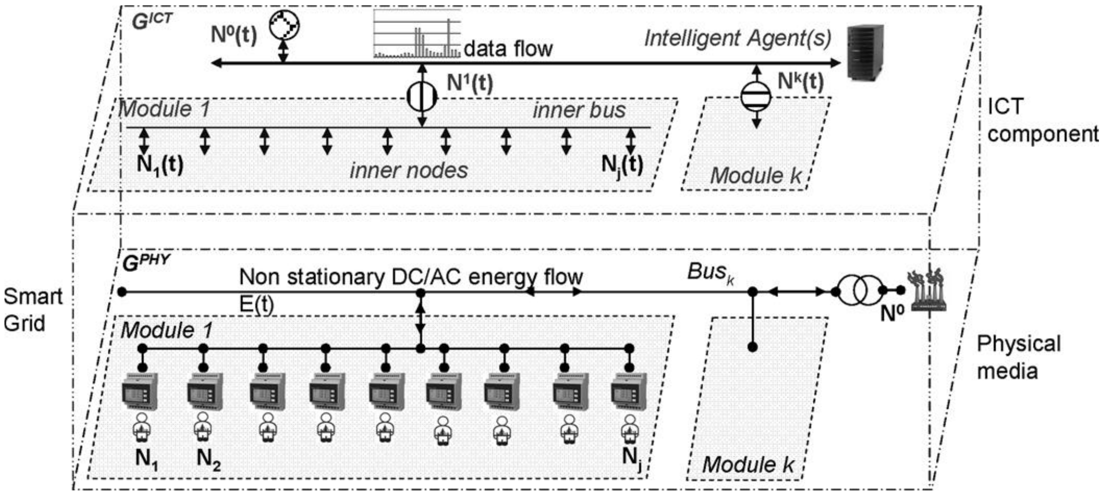


Figure 20: DC microgrid with dynamic partitioning capability[25]

Microgrid fission is incorporated with networked/clustered microgrids, which have the capability of independently operating and integrating into a single cluster at predicted or unpredicted load demand ramp-ups. This technique is especially ideal in operating existing distribution systems, redefined as clustered microgrids. According to [74], any kind of microgrid (AC, DC or hybrid) microgrid recommended to be connected to a common bus to satisfy common resiliency requirements of each microgrids as follows.

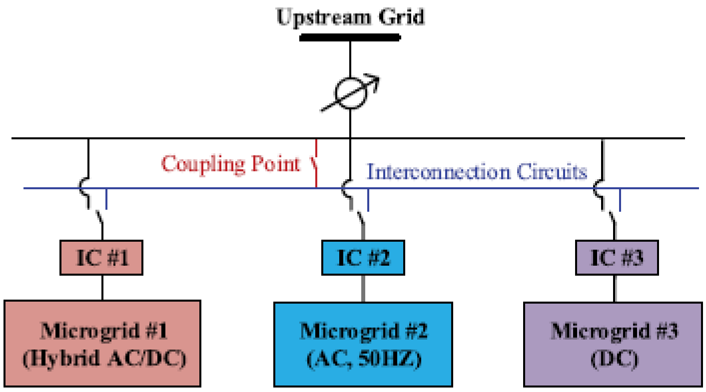


Figure 21: Networked microgrid architecture[74]

To implement this scenario, each microgrid should contain interconnections set up between neighbor grids, islanding detection capability, grid forming capability with proper droop controls individually. In most updated versions of urban infrastructure development, microgrids are developed as concentrated energy hubs which have interconnections between petroleum gas distribution as well as heat distribution networks as mentioned in [74], [75]. Figure 22 describes the structure of such systems.

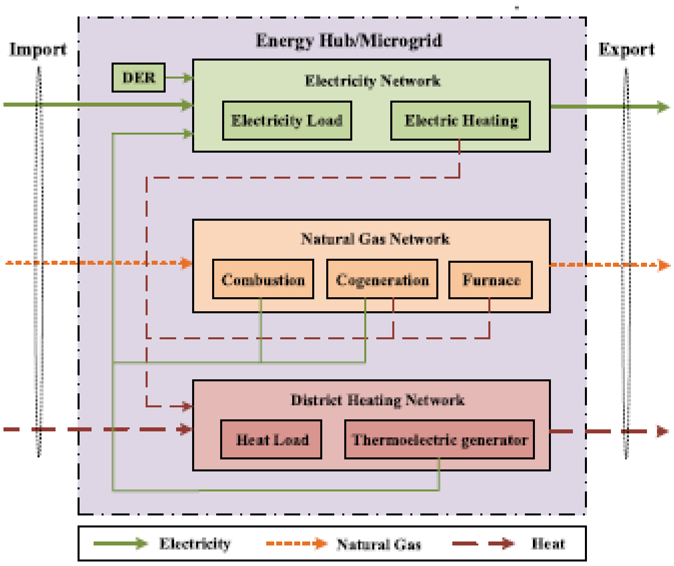


Figure 22: Microgrid as an energy hub[74]

2. Long-term Resilience

In the context of long-term resilience, whether resilience and equipment resilience are discussed.

At extreme whether conditions, microgrid operation can be interrupted due to flooding, winds and lightening. Most of the short-term resilience improvement mechanisms are designed to withstand microgrid operation in extreme whether conditions, but some of the researchers like to associate whether forecasts into account with controlling aspects. As an example, [76] suggests a proactive scheduling methodology for microgrid operation to face extreme flooding events. In this method, three major aspects are discussed: a) Vulnerability study b) Worst-case analysis and c) Proactive scheduling. This methodology converges into optimal power flow schedule for each case based on interrupted equipment as well as prioritized loads in the time frame. Similarly, [24] discusses formation of microgrids by disintegration of distribution system into smaller scale sub-grids.

In the context of equipment resilience, [8] suggests a data driven approach with controller involvement to monitor equipment conditions and build up a stochastic model parameterizing equipment failure probability and scheduling microgrid operation based on those data as well. Especially, [12], [77] discusses about approaches to parameterize inverter operational flexibilities and build up forecasts on probable failures based on their operational conditions.

2.6.3. Tertiary Control Strategies

Tertiary controls are mainly related to main grid level controls such as system frequency and voltage control etc. In the case of networked microgrids, tertiary layer is required to organize overall system control with secondary controls discussed above, implemented in the networked grid.

3. PROPOSED ARCHITECTURE

UoM-LECO Smart Grid Research Laboratory (SGRL) is one of the key assets of the Department of Electrical Engineering, University of Moratuwa. It was established to conduct smart grid operation related testing and research purposes. This laboratory contains sophisticated equipment related to low voltage microgrid development as tabulated in table 3.

Table 3: SGRL Equipment list

Equipment category	Description
Renewable energy	16kW solar PV installed. • Fronius Symo 4kW inverter 1 Nos- 3phase • Fronius Symo 5kW inverter 2 Nos- 3phase • Fronius Galvo 1kW inverter 1 Nos- 1phase
Energy storage	• RCT 6kW battery storage 2 Nos- 3phase
Loads	• Yokogawa AC electronic load 1kW- 5 Nos • Yokogawa DC electronic load 1kW- 1Nos

The major intention of this research to build up a controller platform that contains capability of operating a microgrid in a sustainable and resilient way. To develop this controller, the laboratory equipment established in SGRL were decided to be chosen as major DERs of the system. This chapter describes the proposed architecture for this system.

3.1. Introduction

As mentioned earlier, the existing system is solely based on solar PV generation and grid power as power inputs and battery systems as energy storages. To model variable loads, AC/DC electronic loads are established. The overall single line diagram for the system is shown in figure 23.

The overall power network contains 3 sub distribution buses. And these three are connected into a common AC bus. This common bus is coupled with the 400V/50Hz AC main grid.

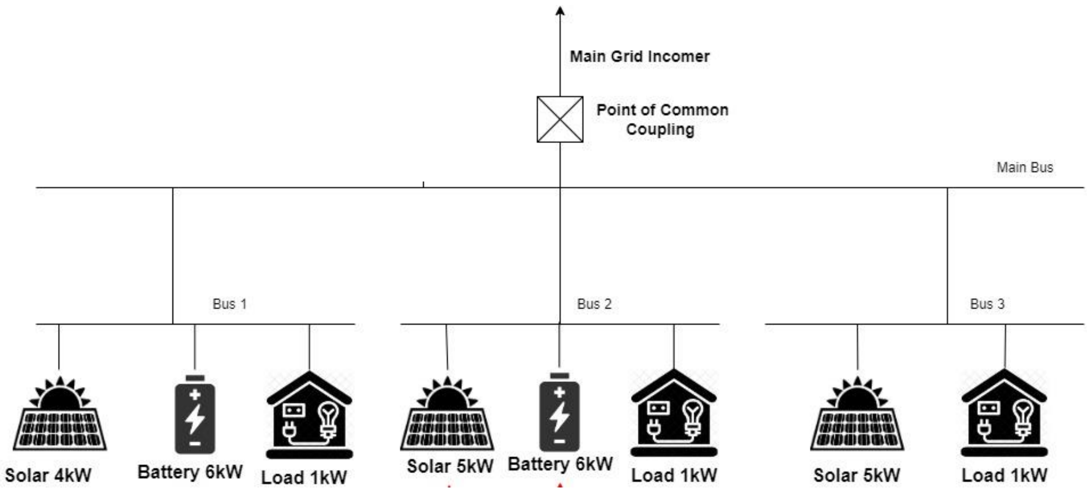


Figure 23: Existing single Line diagram for the system.

The existing battery banks are not capable of forming the grid, due to their control hardware structure. Since, the main proposal was to add an appropriate grid forming inverter (GFI) to the system and then add the controls to the system.

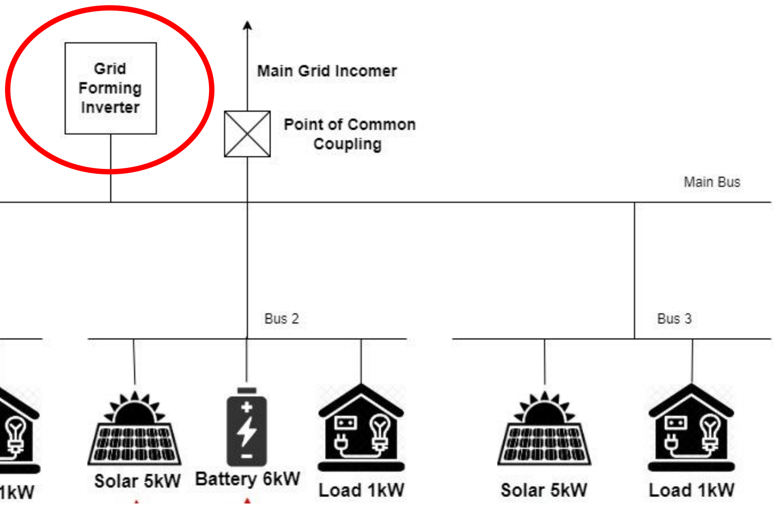


Figure 24: Proposed power architecture for the system.

The control structure is implemented as a hierarchical structure. Since primary controls are already implemented at equipment level, our main target was to implement microgrid central controller to integrate secondary level controls into the system. Tertiary level is managed by the utility grid as usual. Figure 25 suggests the hierarchical control structure suggested for the system. The major functionality of the secondary layer is to implement EMS algorithm separately for two operational modes and operate microgrid in sectional islanded mode in faulty conditions.

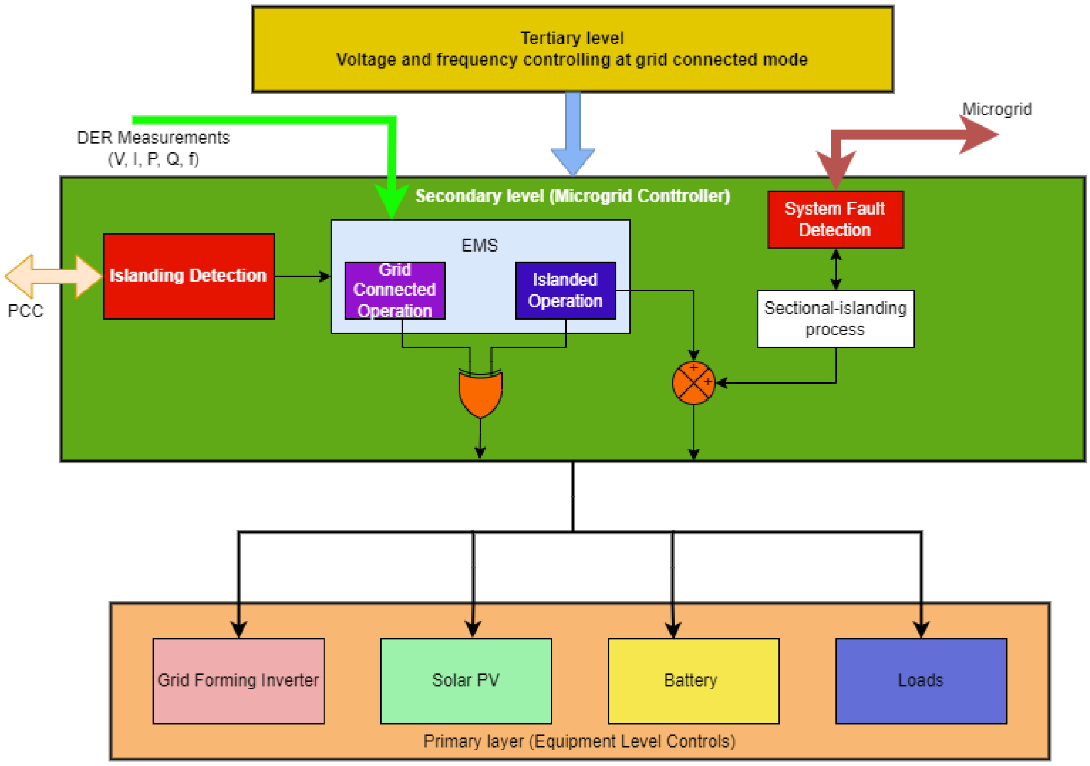


Figure 25: Proposed control architecture for the microgrid.

3.2. Functionalities

In this microgrid controller, major control functions are implemented in secondary later. Two major functionalities are discussed in this scenario.

1. Function of EMS (Improved sustainability aspect)
2. Sectional-islanding process (Improved resiliency aspect)

3.2.1. EMS Functions

EMS function is built upon two major operational modes: grid connected and islanded. Operational algorithms are shown in figure 26. In this control, the most important strategy is to control each sub distribution bus separately under control algorithm.

In this EMS, a rule-based algorithm is selected for the system due to minimize computational power and convenience of implementation. The controller measures solar PV power output, load levels and state of charge percentage (SoC%) as the input measurements and runs the rule-based algorithm for provided operational strategies.

In grid connected operation, the controller calculates power surplus inside the grid for Δt period and if it is positive, the surplus is then directed to the batteries. Before that, the controller measures battery SoC and decides whether the power can be directed to the batteries.

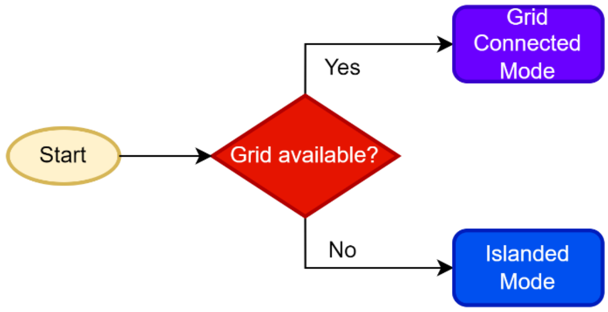


Figure 26: Operational mode selection.

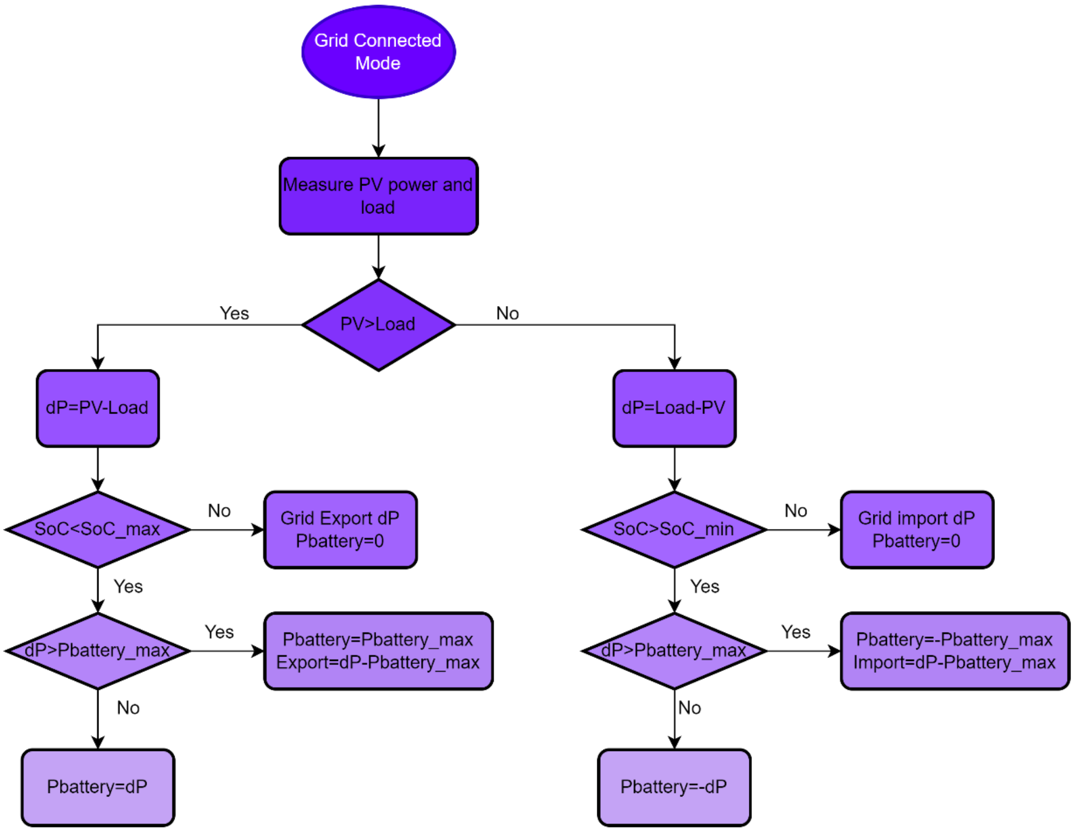


Figure 27: Operational algorithm for grid-connected mode.

According to this flowchart, the controller first calculates the power surplus in the system, and if it is positive (excessive PV power), then it checks the SoC of the battery. If the battery is full, total power surplus is directed to the grid. If batteries have space, then the controller checks whether the power surplus is higher than the battery maximum charging power. If this condition is satisfied, the battery is charged at its full power and excessive power is directed to the grid. If not, battery is charged at available power surplus, without grid export. On the other hand, if the PV penetration is not satisfactory for the load, controller checks the availability of batteries and commands them to release power. If not, total vacant power is catered by the grid. In case of battery availability, the controller checks whether the vacant power is higher than the maximum battery discharge power. If so, battery is discharged in its maximum power and remanent power is imported from the grid. When the power void is lower than battery maximum power, it is totally served by the battery.

The system goes into islanded mode when the main grid is unavailable. Microgrid controller detects the unavailability of the grid and disconnects it from the PCC, changing the control mode from grid connected mode to islanded mode. Islanded mode control algorithm is shown below.

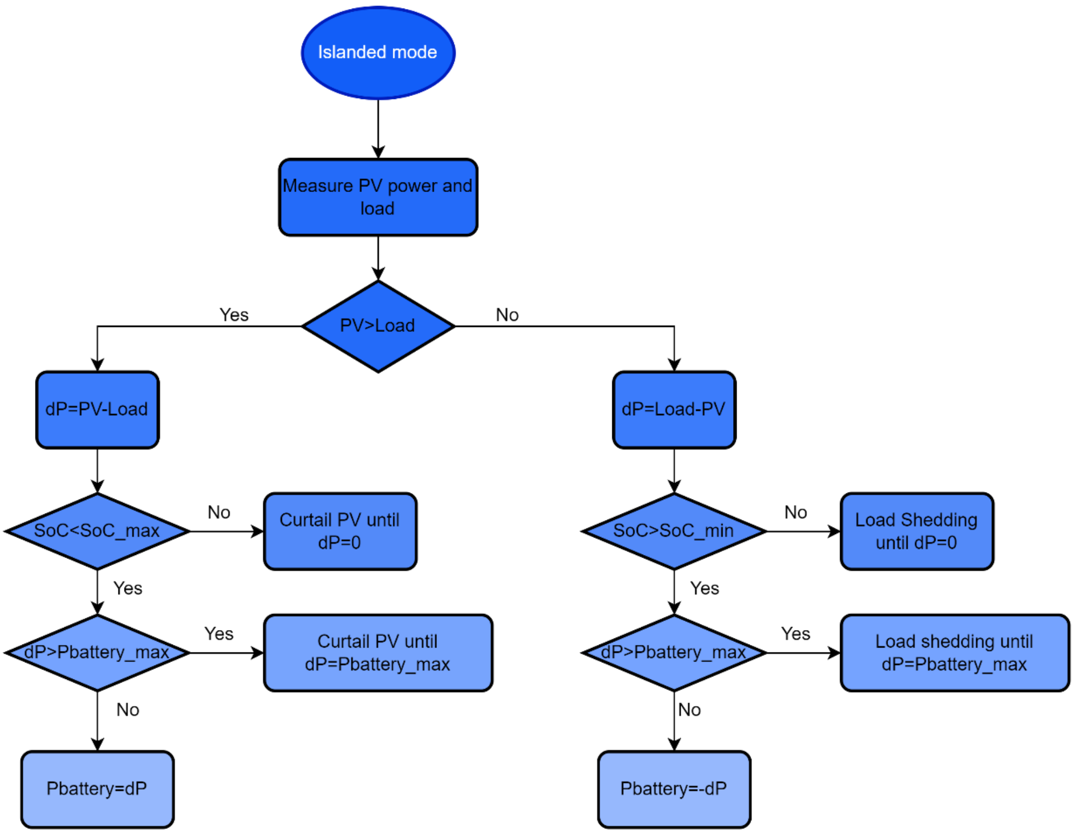


Figure 28: Islanded mode control algorithm.

Like the grid connected mode, the PV power and the load are measured in this mode also. After that, if the PV penetration is higher, the SoC level of the battery is measured and if the battery space is not free, PV power is curtailed until load is fully served by the PV. If there is enough space and excess power is higher than battery power rating, PV power is curtailed until power excess is equal to the battery power rating. If not, vacant power is directed to the battery with its availability. If PV power is not enough to cater loads, load shedding strategy is implemented. If the battery is discharged below its operational limit, loads are shed until the load can be provided by the PV power. In here, non-essential loads are adjusted until generation and demand is balanced. If the battery can provide power, but the load is higher than the battery power rating, again the load shedding is implemented until the load is equal to the battery power. If the remaining load (Total Load-PV) is well below the battery maximum power, it is catered by the battery.

3.2.2. Sectional-Islanding Control

Since this control algorithm is capable of bus-wise control in islanding mode, improved resiliency is ensured by operating any bus in a separated control. This scenario is implemented when the grid goes to faulty situations in islanded mode. Assume a fault at the interconnection of two buses, the main bus and Bus1 (figure 29). To avoid interruptions caused by these kinds of failures in the system operation, sectional islanding mode is introduced. In this subject system, Bus 1 and 2 can be operated according to this since they contain battery banks.

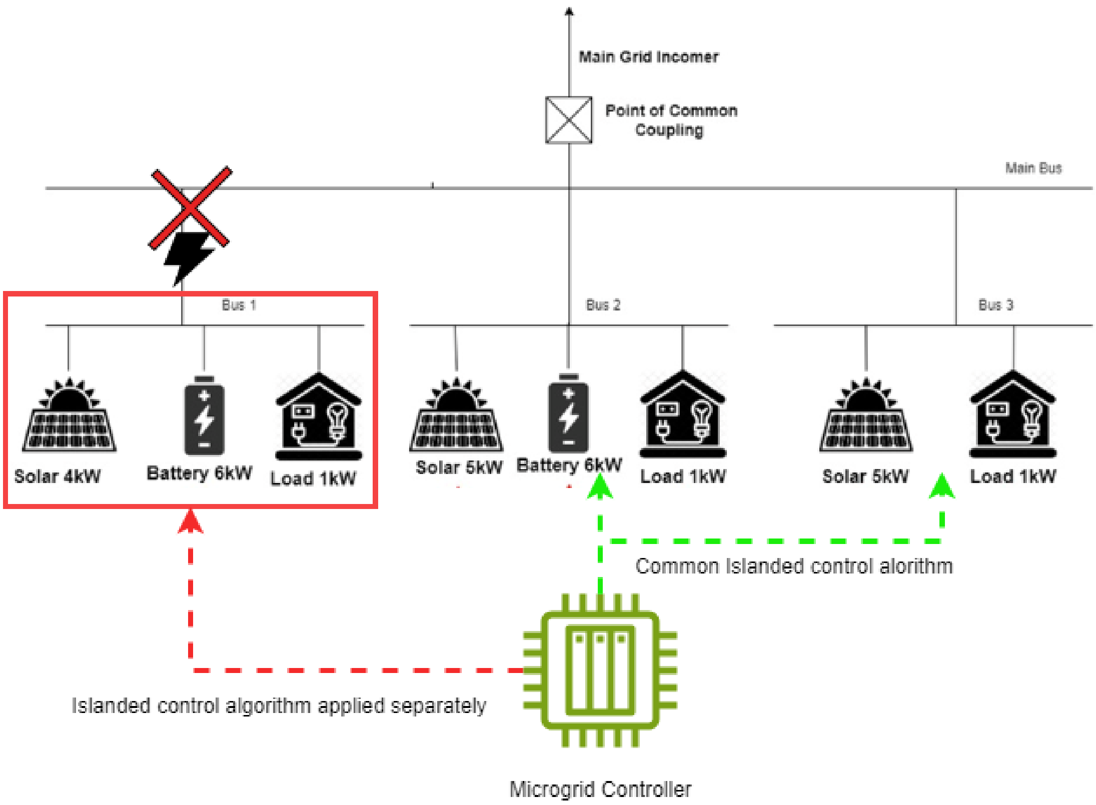


Figure 29: Sectional islanding mode description.

4. DESIGN AND MODELLING

In this chapter, the process of designing and simulating the proposed architecture is described.

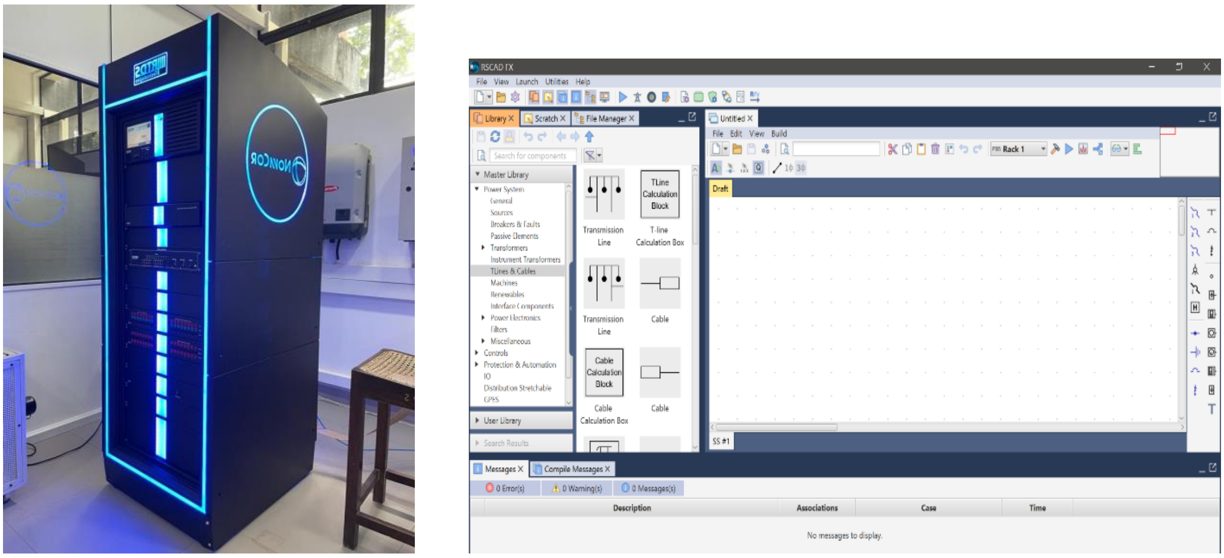
One of the key identities of this research is to adopt Real-Time Simulations (RTS) in the modelling process. Usage of RTS in the design level gives benefits like,

1. Real time response checking
2. High speed simulation capability
3. Convenience of output visualization
4. Hardware in Loop Capability

The facilitation of RTS is provided by a sophisticated hardware+ software environment called Real-Time Digital Simulator (RTDS)

4.1. Real Time Digital Simulator (RTDS)

RTDS is a powerful simulation environment, specifically designed for electrical engineering related applications. This environment is empowered by high-performance hardware equipment, modelling software tool, communication interfaces, digital and analog I/O interfaces, high power interfacing boards as an integrated platform to perform real time simulations.



(a) RTDS Hardware in SGRL

(b) RSCAD software environment

Figure 30: RTDS and RSCAD

4.2. Microgrid System Modelling

The microgrid system model contains 4 major components,

1. Solar PV model
2. Grid Tied Battery Model
3. Grid Forming Inverter Model
4. Load Model

The overall simulation done using RSCAD is shown in figure 31.

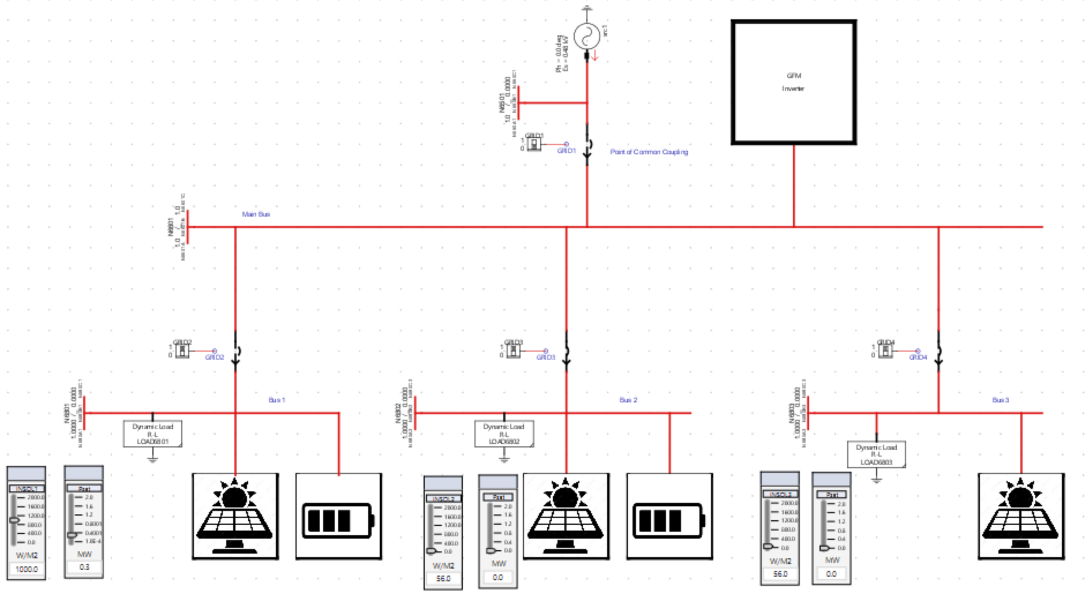


Figure 31: RSCAD simulation of the system.

The simulation consists of variable AC loads that are to be adjusted by slider options. Solar PV inverters are fixed at each bus and all of them are designed to adjust PV array temperature and PV irradiation for each PV system. Battery System is internally controlled by the central controller, no independent variables related to battery operation is considered in the simulation. In other words, the performance of the controller is only checked while the loading and irradiation is changed at each bus.

4.2.1. Solar PV Model

Basic model of solar PV inverter contains 3 major components.

1. PV array model
2. Inverter model
3. Inverter controller model

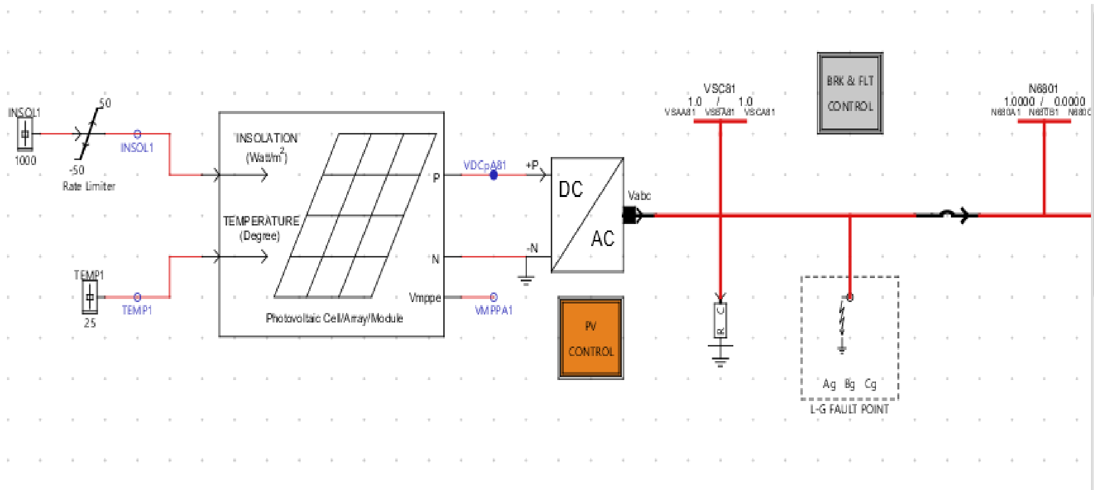


Figure 32: Overall solar PV model

4.2.1.1. PV Array Model

RSCAD built in PV array model is used here. It takes temperature and solar irradiation as inputs and outputs power according to the array configuration. Configuration contains panel configurations and PV array configurations. The following images show PV array and configuration window.

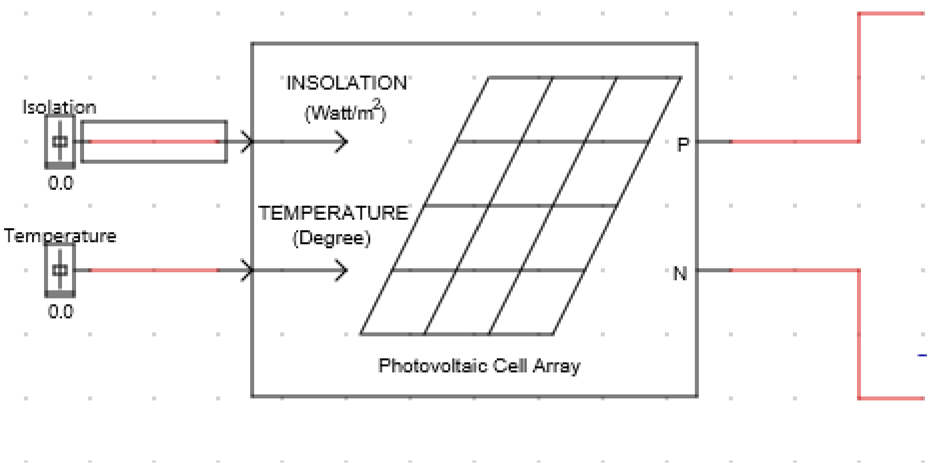


Figure 33: PV array component.

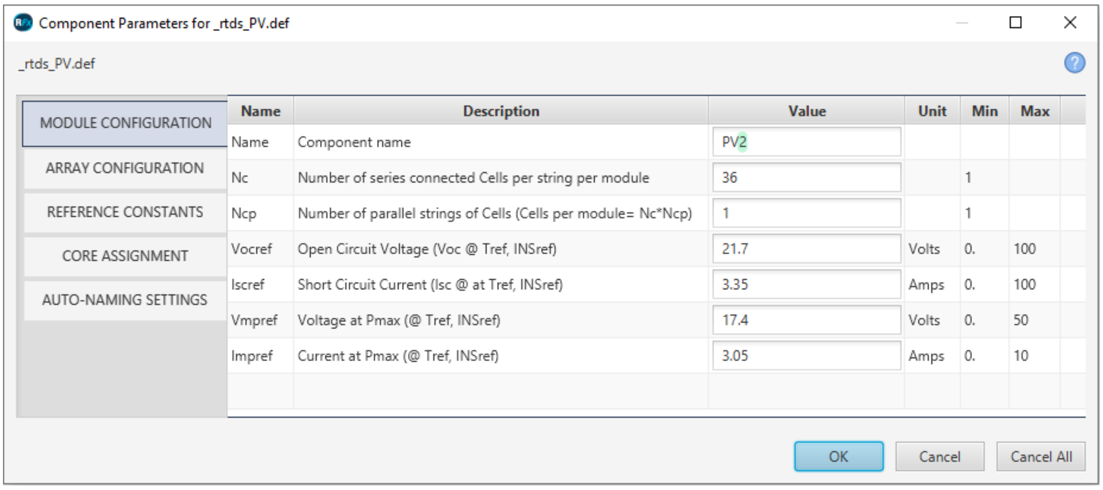


Figure 34: PV array configuration window.

Following configurational data were used to define panel array.

Table 4: PV array configurational data

Nominal Power (P_{nom})		53Wp
Open Circuit Voltage (V_{oc})		21.7V
Short Circuit Current (I_{sc})		3.35A
Maximum power point voltage (V_{mpp})		41.7V
Maximum Power Point Current (I_{mpp})		9.6A
Array Configuration and size (Series X Parallel)	Bus 1 Inverter	115 X 66 (0.4MW)
	Bus 2 Inverter	115 X 66 (0.4MW)
	Bus 3 Inverter	115 X 66 (0.4MW)

4.2.1.2. Inverter Model

Inverter models are built using an average value model (AVM) which is a high-level modelling technique for inverters. Mo power electronic level modelling is considered in this model.

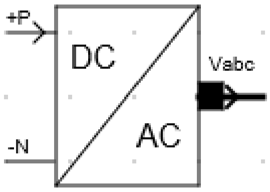


Figure 35: Inverter AVM component

In the configuration window, only reference signals for the PWM switching circuit should be given as inputs to this model.

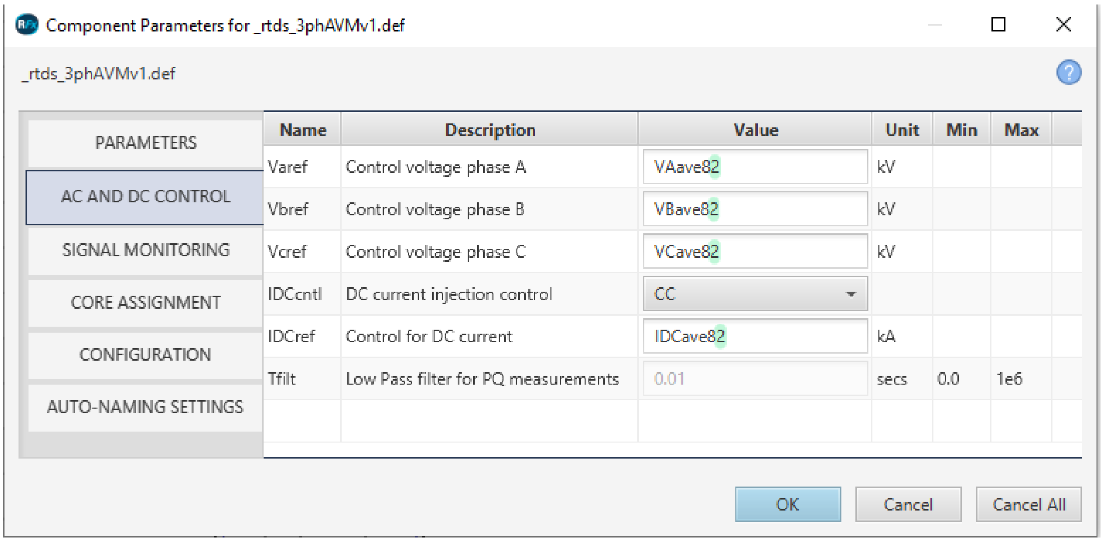


Figure 36: AVM configuration window.

As main parameters, the following are given.

Table 5: AVM configuration parameters

AC side filter resistance	$2 \times 10^{-3} \Omega$
AC side filter inductance	$100 \times 10^{-6} H$
DC side series resistance	$1 \times 10^{-6} \Omega$
DC side filter capacitance	$5\ mF$
DC side current injection resistance	$2 \times 10^{6} \Omega$

4.2.1.3. Inverter Controller

Inverter controller contains dual loop vector control method. Separate path is added to DC bus voltage control.

1. DC bus voltage control

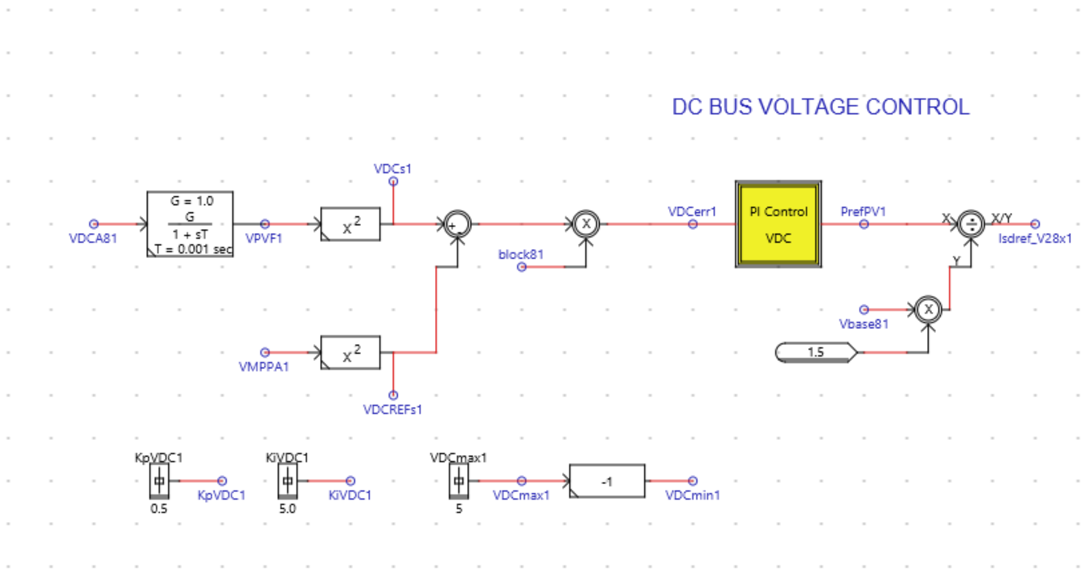


Figure 37: DC bus voltage controller.

MPPT voltage is tracked by the controller to keep DC bus pushing power towards grid. This controller generates reference current d component, which is fed into the current control loop. I_q is usually kept zero.

2. Inner Loop Current Controller

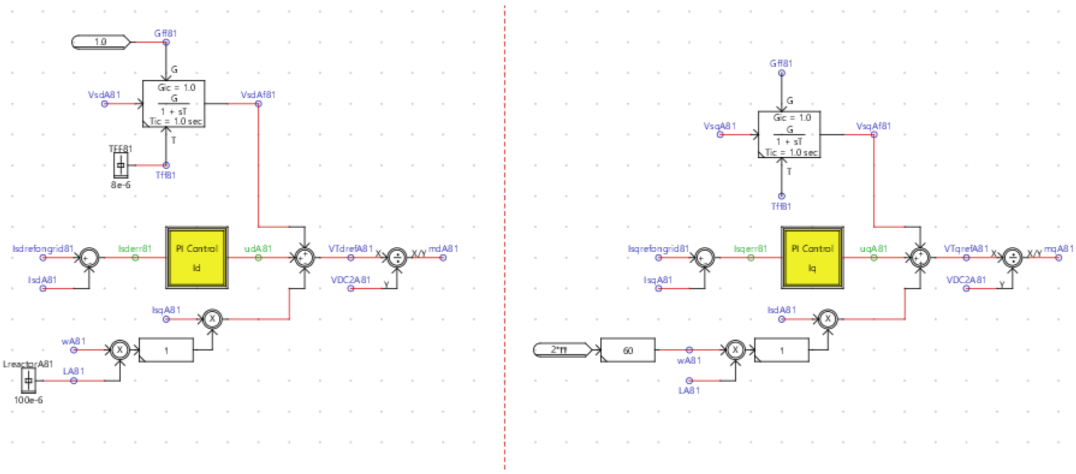


Figure 38: Current control loop

This loop generates reference modulation signals for reference voltage generator loop.

3. Reference signal generator

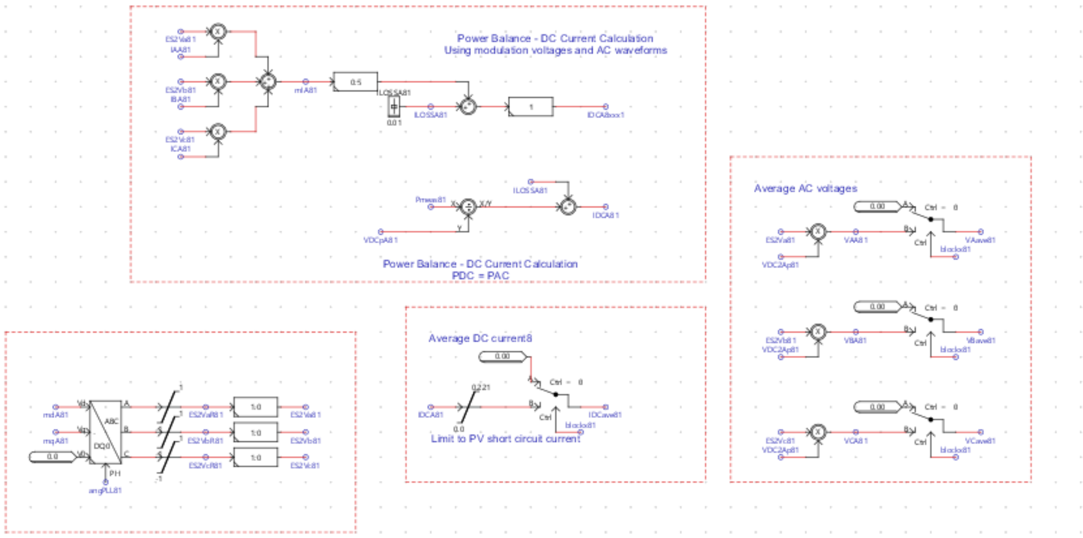


Figure 39: Reference signal generator for AVM.

Generated references are directed to the AVM model.

4.2.2. Grid-Tied Battery Model

This model contains three major parts.

1. Battery model
2. Inverter model
3. Inverter controller

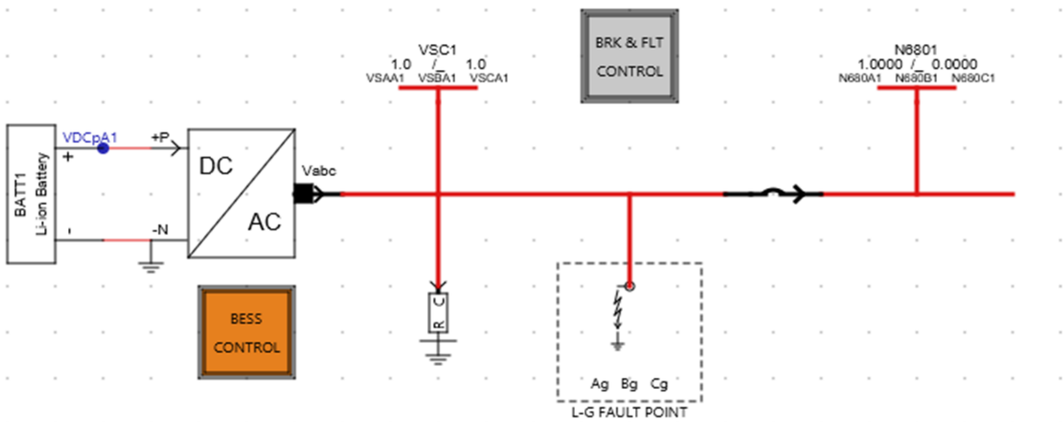


Figure 40: Grid-tied battery model

4.2.2.1. **Battery Model**

Built in Li-Ion battery model is used as the battery model for this simulation. As the only control variable, the initial state of charge is changed at different test cases.

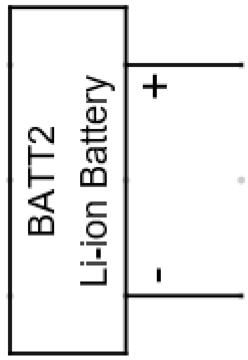


Figure 41: Li-Ion battery model

Battery configuration contains definition of cell parameters, battery stack configuration and signal monitoring details to be defined. State of Charge (SoC) will be the sole measurement internally taken from the battery model.

Table 6: Li-Ion battery model configuration data

Stack size (series X Parallel cells)	250 X 250
Battery Type	Min/Rincon Mora[78]
Capacity	53kW
Initial State of charge	Varied according to the simulation case

4.2.2.2. **Inverter Model**

The same AVM model used in solar PV model is used here as well.

4.2.2.3. **Inverter Controller**

BESS controller is applied in the primary control layer of battery bank control. This contains two major control loops; grid connected PQ control and inner loop dq current control loop.

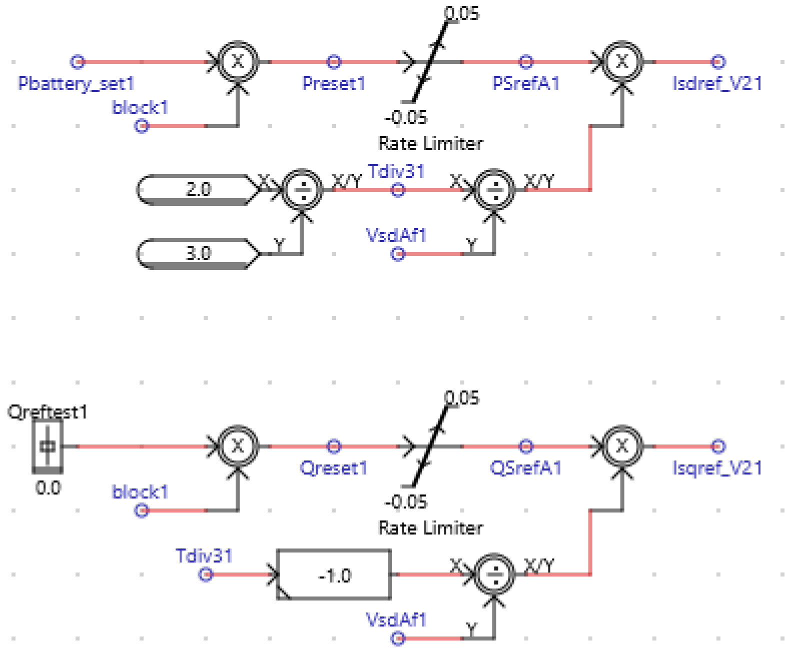


Figure 42: Grid connected PQ control loop.

In this loop, main controller, active power setpoint is directed to the Pbattery_set1 variable as indicated in the figure.

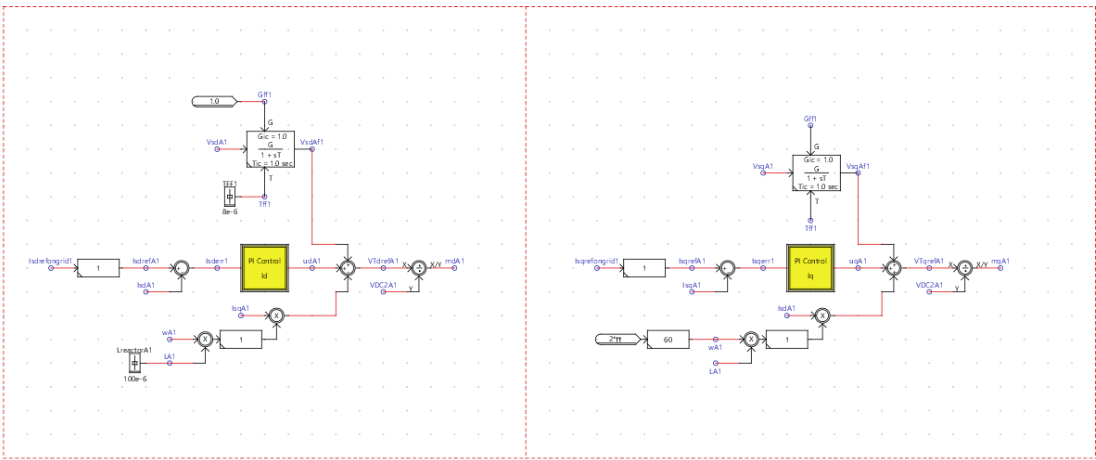


Figure 43: Id and Iq component controller.

Same as PV model, the modulation signals of current control loop output is fed into the AVM model reference generation control loop.

4.2.3. Grid-Forming Inverter Model

Grid-Forming Inverter (GFI) mode contains 2 major components: IGBT bridge and GFI controller model. As shown in the following diagram, the DC side supply is provided by a controllable voltage source. The IGBT bridge is operated according to the implemented controls.

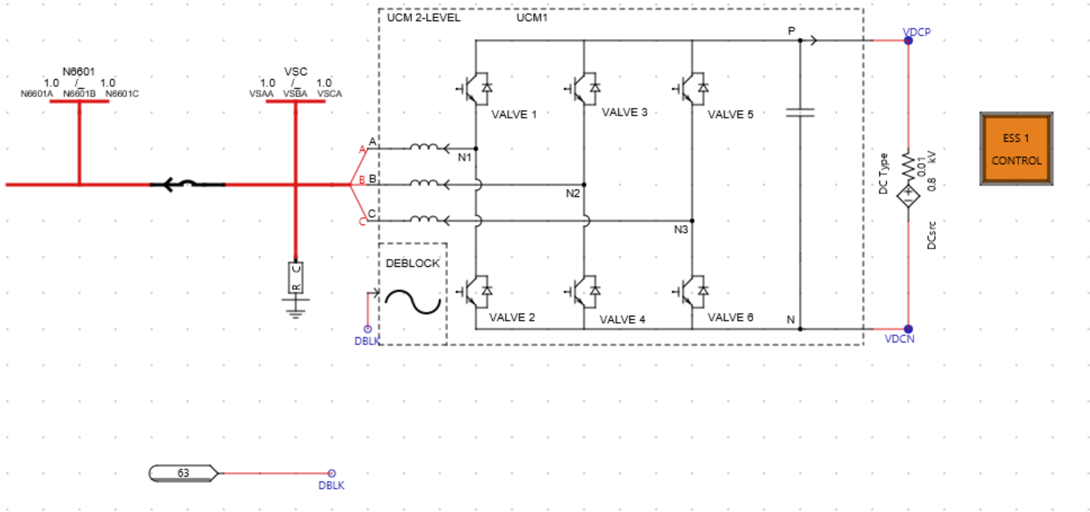


Figure 44: Grid-Forming Inverter model.

4.2.3.1. IGBT Bridge

The IGBT bridge component in RSCAD can be configured to take modulation signals of each phase as inputs and generate 3 phase output accordingly. IGBT bridge semiconductor characteristics should be entered to correctly generate output.

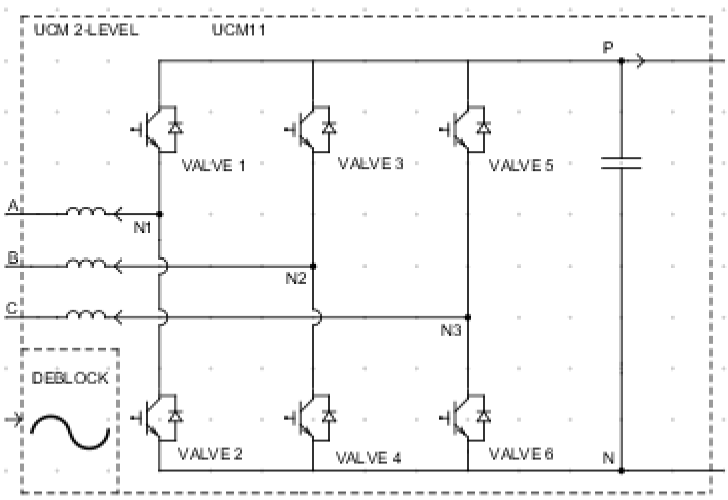


Figure 45: IGBT bridge

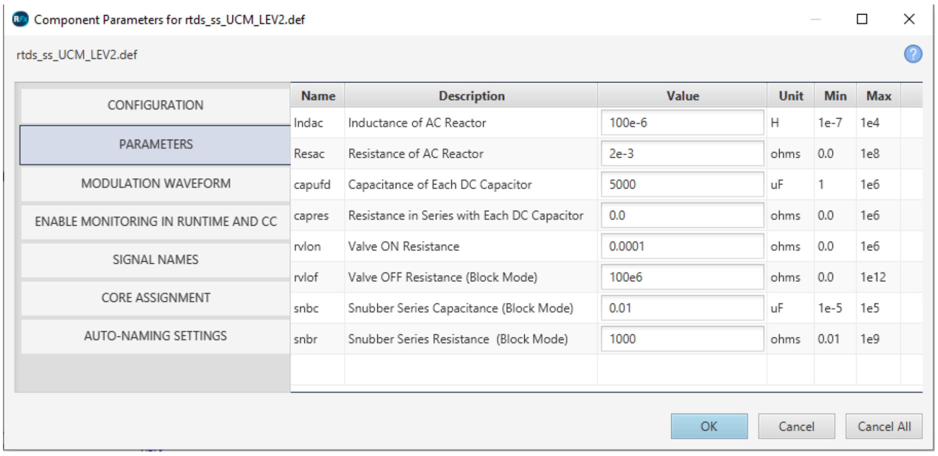


Figure 46: Configuration window of IGBT bridge component.

IGBT data were given as default and input modulation signals were directed from GFI controller.

4.2.3.2. GFI Controller

Vector control method is used here as well. Major two control modes are implemented in this control: grid connected PQ control and islanded droop control.

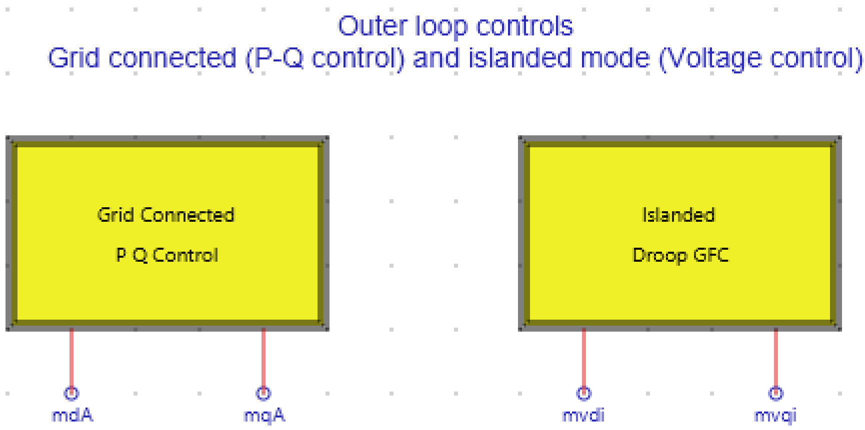


Figure 47: Main control modes.

In grid connected PQ control, the GFI is operated as a normal energy storage which is operated at a minimum SoC limit and charging and discharging at a constant power range.

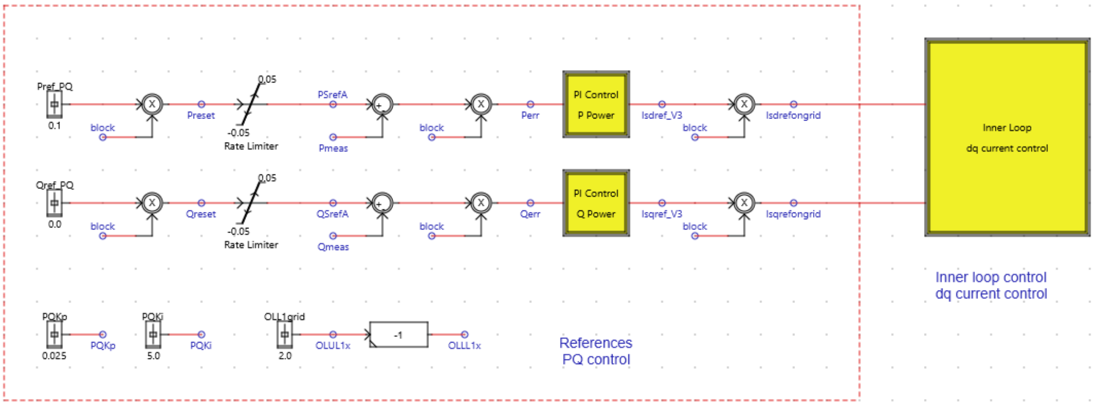


Figure 48:Grid connected PQ control.

PQ sliders are used to set power outputs to the GFI. As usual, the inner current control loop contains Id and Iq control.

In islanded droop control, phase angle control is done by active power controlling setpoints. Voltage magnitude controlling is done by reactive power controlling converted in the dq frames and then it is directed to ABC frame.

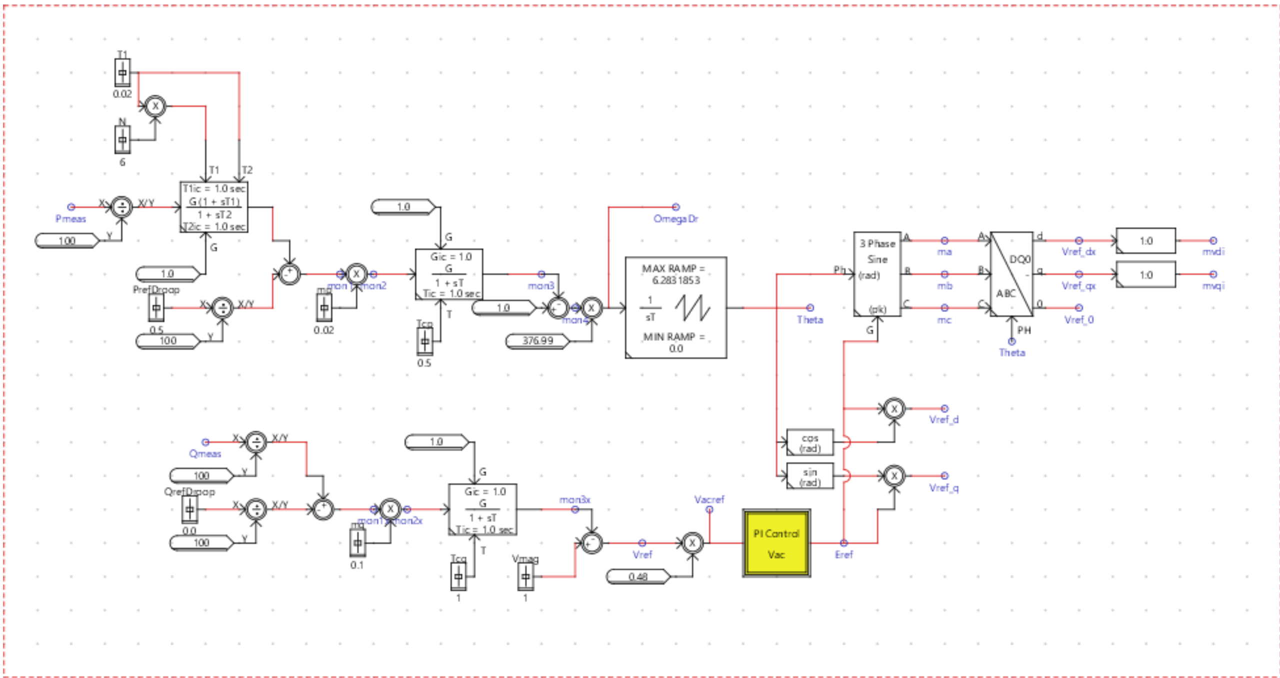


Figure 49: Islanded droop control.

4.2.4. Variable AC Load Model

Another variable parameter in the microgrid simulation is different loading conditions. This condition is modelled using dynamic AC load model implemented in the system.

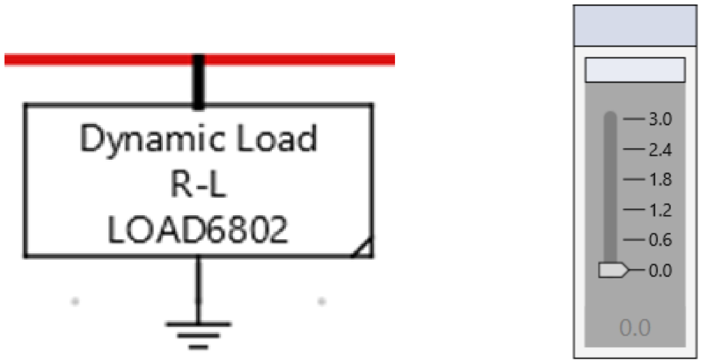
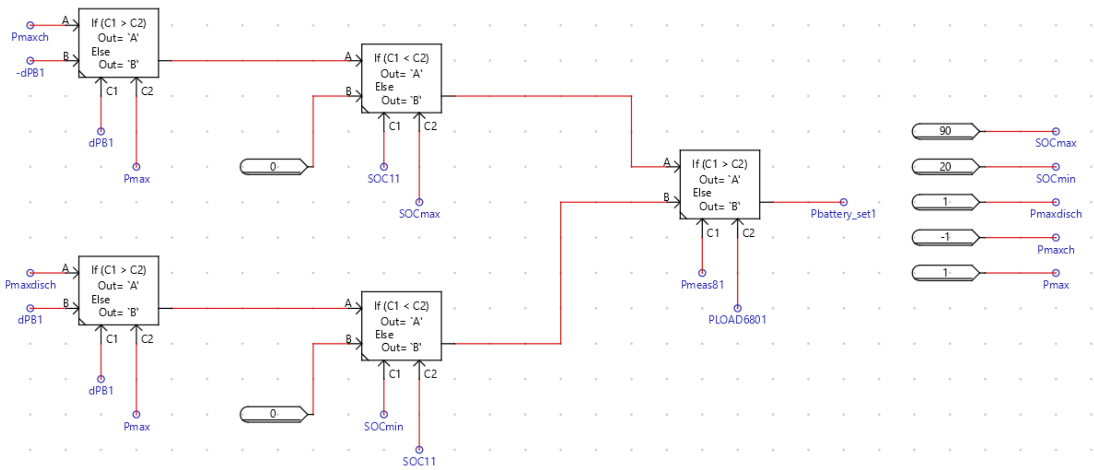


Figure 50: Dynamic AC load model and control slider.

The loading conditions are changed at run time using sliders as shown in the above figure.

4.3. Algorithm Implementation

The algorithm discussed under section 3.2 is implemented as separate two cases as grid connected and islanded modes. The algorithm is implemented for each sub distribution bus using simple if conditions, to operate as a bus-wise controller. This means that the algorithm considers each sub-distribution bus separately into account



at the controller operation.

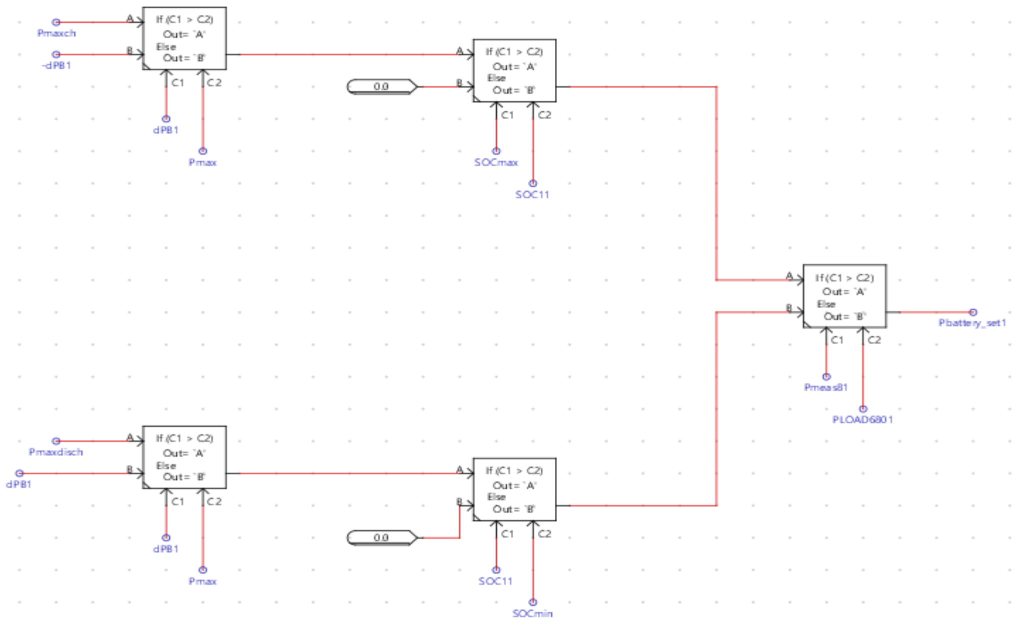
Figure 51: Grid connected operation of Bus 1

Bus 2 has a similar algorithm for operation. Since bus 3 does not contain any battery banks, it operates according to the general energy balance operation. The operational limits for battery banks are defined as follows.

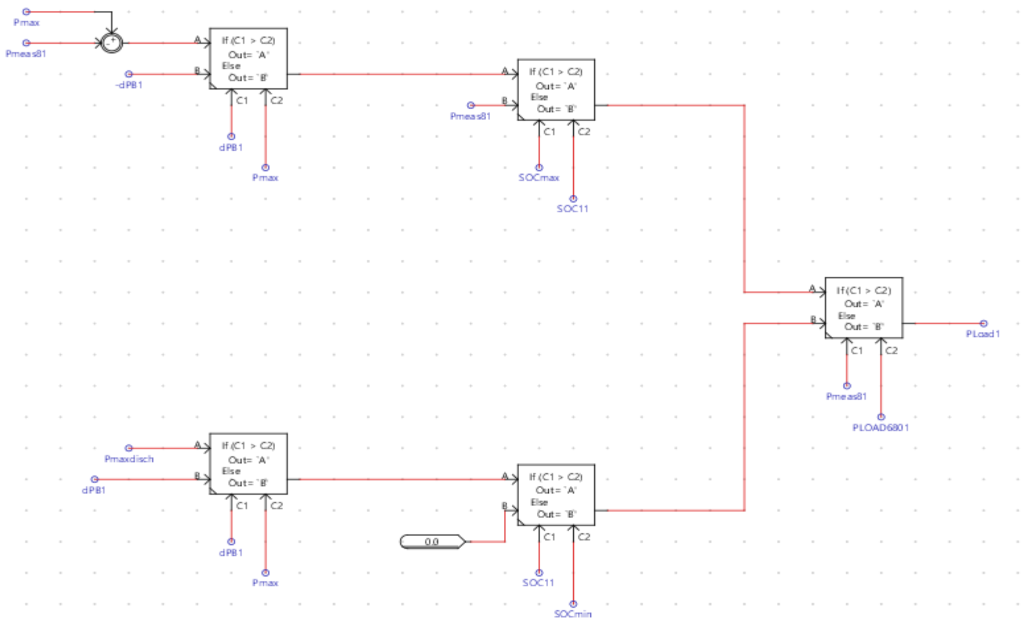
Table 7: Operational constraints of battery bank

SoC Limit	20% - 90%
Charging/discharging limit	1MW

In a similar fashion, islanded control algorithm is developed as following diagram.



(a) Battery Power Control Logic



(b) Load Controlling Logic

Figure 52: Islanded control algorithm.

For sectional islanding process, the same algorithm is used to operate subjected bus separately.

4.4. Case Studies and Results Discussion

To validate the simulation, each case study was validated using different scenarios. The case study description is shown in the table below.

Table 8: Case Study Details

Operational mode	Case Number	Solar Irradiation (W/m^2)	Loading (MW)	Battery SoC% level	Remarks
Grid Connected	1	1000	0.1	90	Battery full, high irradiation, lightly loaded
	2	1000	0.1	50	High irradiation, low SoC, lightly loaded
	3	~0	0.6	90	High SoC, low irradiation, high loading
	4	~0	0.6	20	Low SoC, low irradiation, high loading
Islanded Operation	5	1000	0.3 to 0.12	90	PV curtailment
	6	1000 to 400	0.6	20	Load control

The simulation results are discussed in the following, which are related to a single bus.

4.4.1. Case 1 (Irradiation=1000 W/m^2, Load=0.1 MW, SoC=90%)

In this case, the battery at its defined maximum charge level and the system is lightly loaded. This means that the solar power generated is directed to the load and excess is directed to the grid. As per the simulation results, the following data is acquired.

Table 9: Case 1 Simulation Results

Bus No.	1
Solar PV power	0.36 MW
Load	0.1 MW

Battery Power	0 MW
Grid Export	0.26 MW

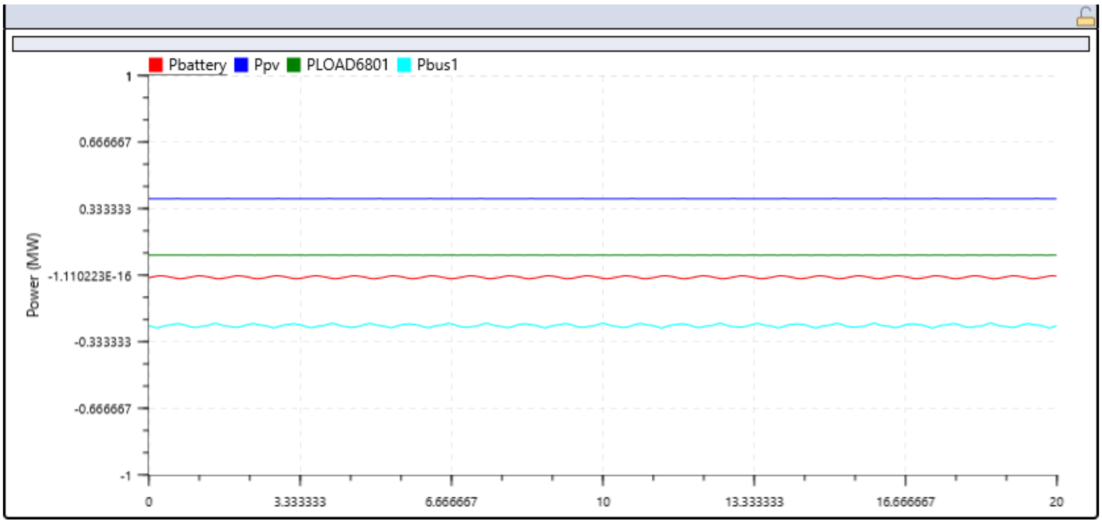


Figure 53: Case 1 Simulation results.

According to the results, PV generation is used to serve load and the rest is directed to the grid. Since the battery is charged to its maximum level, the battery does not absorb any power.

4.4.2. Case 2 (Irradiation=1000 W/m^2, Load=0.1 MW, SoC=50%)

In this case, the battery is partially charged, and the system is lightly loaded. This means that the solar power generated is directed to the load and excess is directed to the battery and if the solar irradiation exceeds battery power limit, excess is exported to the grid. As per the simulation results, the following data is acquired.

Table 10: Case 2 Simulation Results

Bus No.	1
Solar PV power	0.36MW
Load	0.1 MW
Battery Power	0.26 MW
Grid Export	0 MW

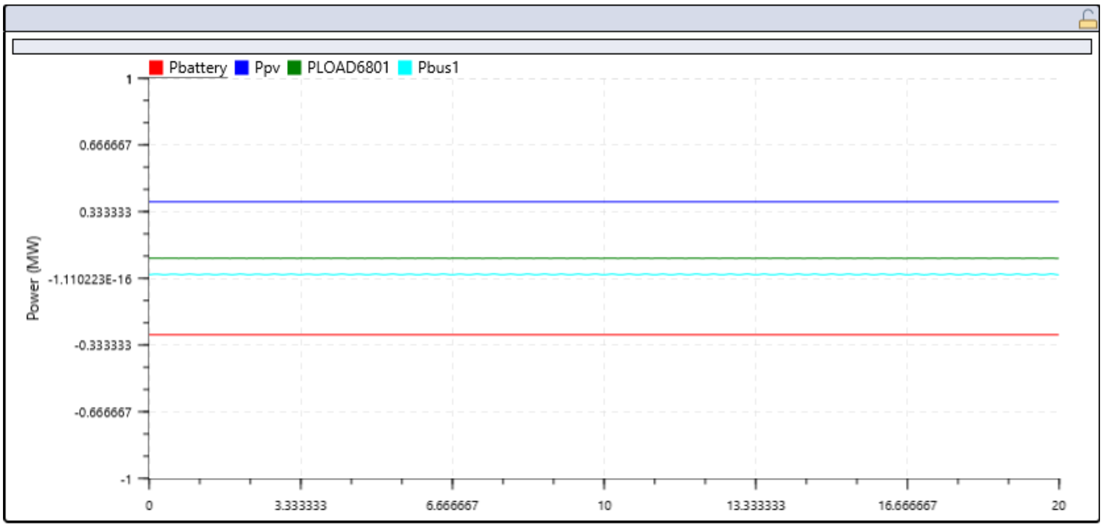


Figure 54: Case 2 Simulation Results

According to the results, PV generation is used to serve load and the rest is directed to the battery. Since the battery maximum power is 1 MW, vacant power does not export to the grid, until it is fully charged.

4.4.3. Case 3 (Irradiation~0 W/m^2, Load=0.6 MW, SoC=90%)

In this case, the battery is fully charged, and the system is highly loaded compared to previous cases. Since battery can sufficiently provide up to 1 MW, the expected result is to provide battery power to the load, without gird export. As per the simulation results, the following data is acquired.

Table 11: Case 3 Simulation Results

Bus No.	1
Solar PV power	~0 MW
Load	0.6 MW
Battery Power	0.6 MW
Grid Export	0 MW

The RTDS simulation results are visualized as follows.

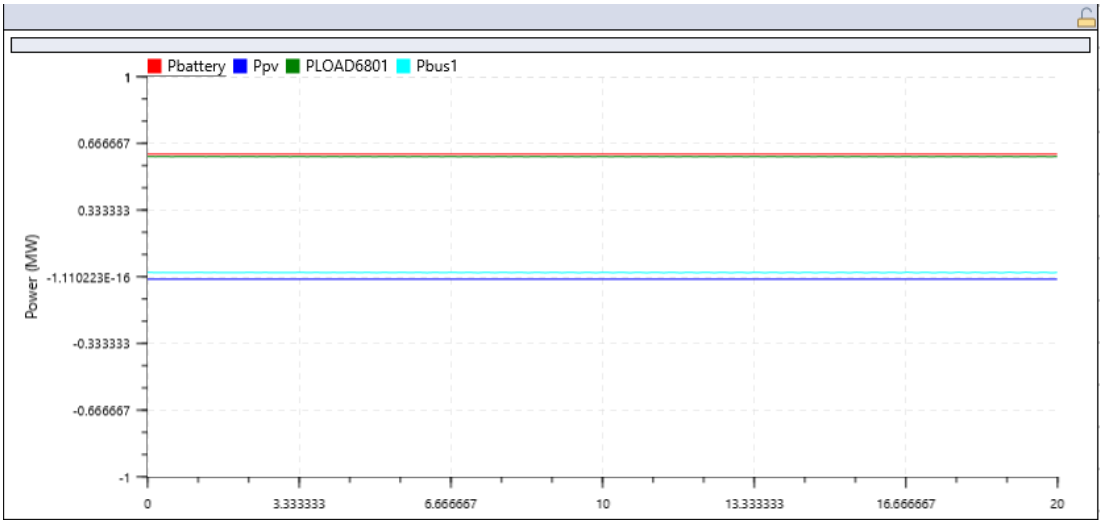


Figure 55: Case 3 Simulation Results

As per the expectation, load at bus 1 is totally served by the battery without any grid export.

4.4.4. Case 4 (Irradiation~0 W/m^2, Load=0.6 MW, SoC=20%)

In this case, the battery is at its lower SoC setpoint, and the system is highly loaded compared to previous cases. Since battery is restricted to be discharged, the expected result is to provide grid power to the load. As per the simulation results, the following data is acquired.

Table 12: Case 4 Simulation Results

Bus No.	1
Solar PV power	~0 MW
Load	0.6 MW
Battery Power	0 MW
Grid Import	0.6 MW

The following result shows visualized diagram of energy balance at bus 1.

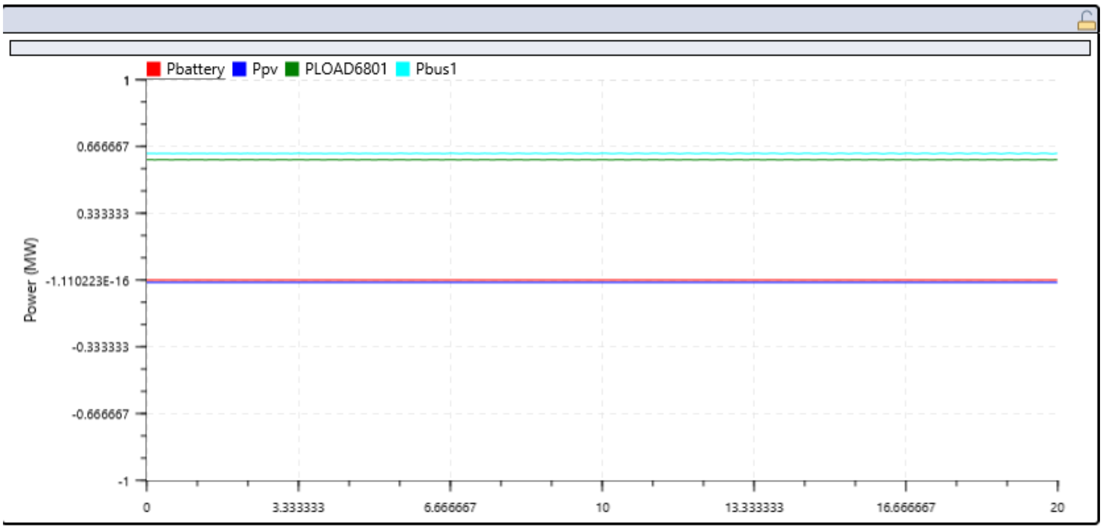


Figure 56: Case 4 Simulation Results

According to the results, load at bus 1 is totally served by the major grid.

4.4.5. Case 5 (Islanded Case, Irradiation=1000 W/m^2, Load= 0.3 to 0.12 MW, SoC=90%)

This case explains the islanded scenario of microgrid. In a fixed irradiation and full battery scenario, load varies from 0.3 MW to 0.12 MW. The expectation of this scenario is to curtail PV power according to the load since the vacant power cannot be directed to anywhere. Simulation results are shown as follows.

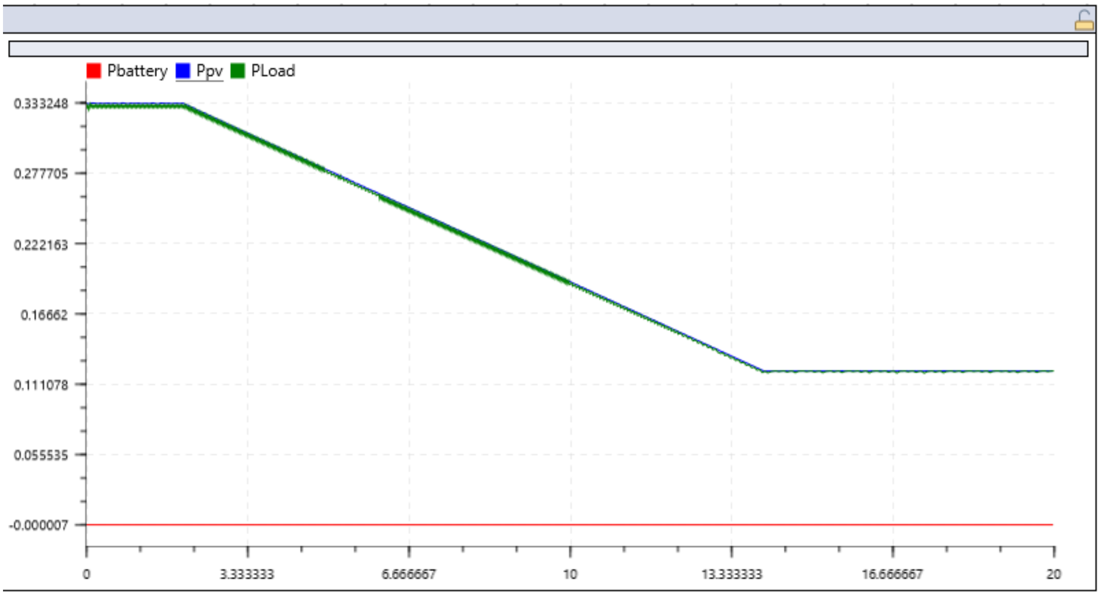


Figure 57: Case 5 Simulation Results

As per the results, the PV power follows the load and battery is not charged by any means since it is fully charged.

4.4.6. Case 6 (Islanded Case, Irradiation=1000-400 W/m^2, Load=0.6 MW, SoC=20%)

In this case, the battery is kept at the lower level of its SoC, and solar irradiation is changed from 1000 to 400 W/m^2 and initially load is kept at 0.6 MW. Since battery is at its lower SoC level, it does not contribute to the load by any means and hence it is expected to curtail load accordingly to the solar penetration.

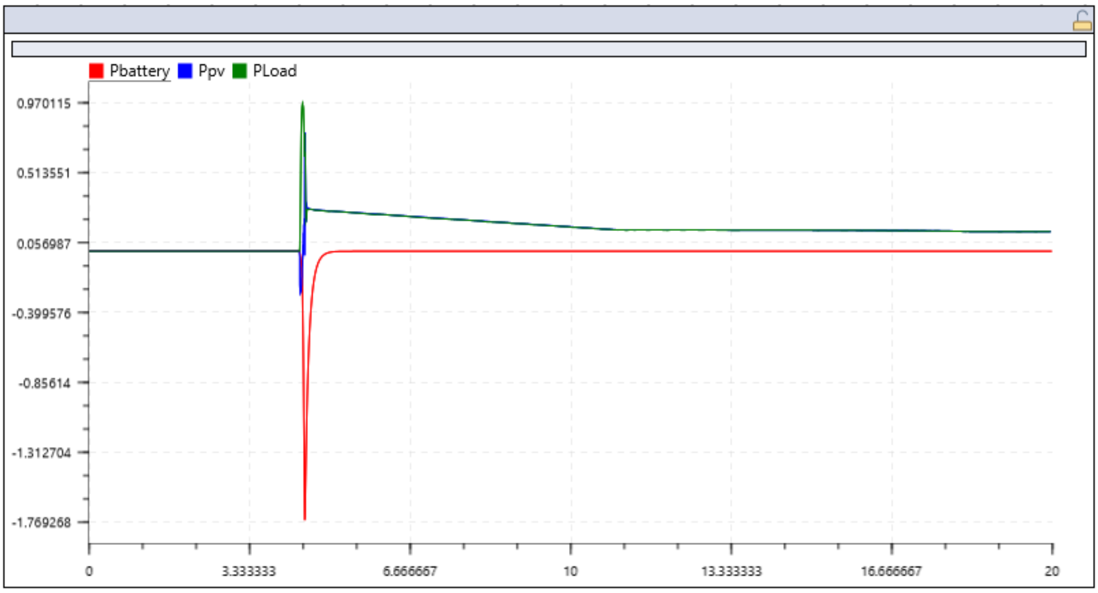


Figure 58: Case 6 Simulation Results

Simultaneously, in the full system islanding, the following voltage profile was recorded. It shows the stable transition of grid connection to islanded mode.

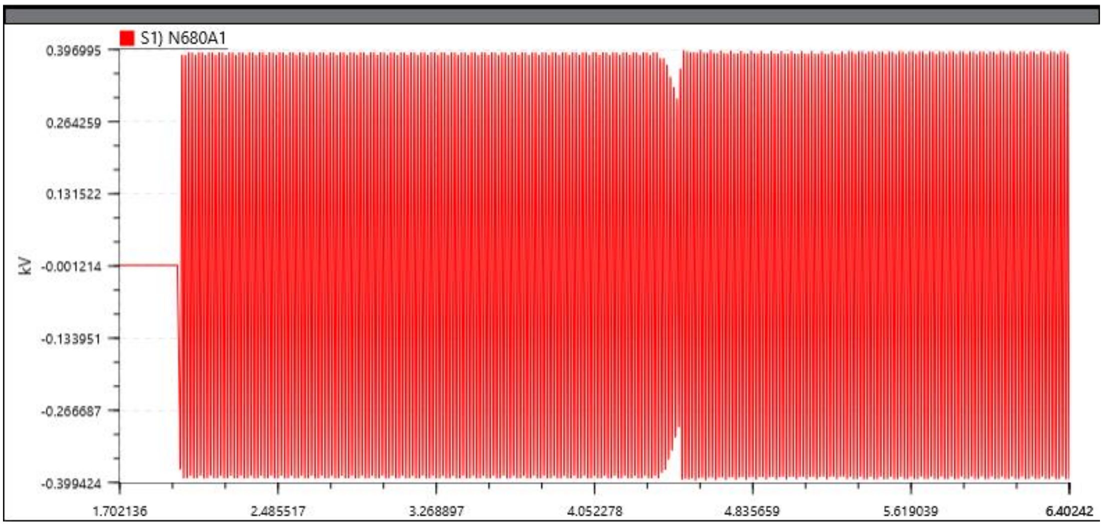


Figure 59: Voltage behavior of the system at islanding

4.5. Sectional Islanding Scenario

For this simulation, bus 1 was separately isolated and an operational algorithm was implemented for the bus 1. In sectional islanding case, bus 1 is desired to be operated as a separate island according to the same algorithm provided in the main grid operation.

To test this operation, case 5 and 6 implemented in full system control scenario was used in this as well. Simulation cases were implemented for bus 1 operational control.

Since this scenario is implemented as a further islanding case, the voltage transient is considerably higher than the previous case. Figure 60 shows this scenario.

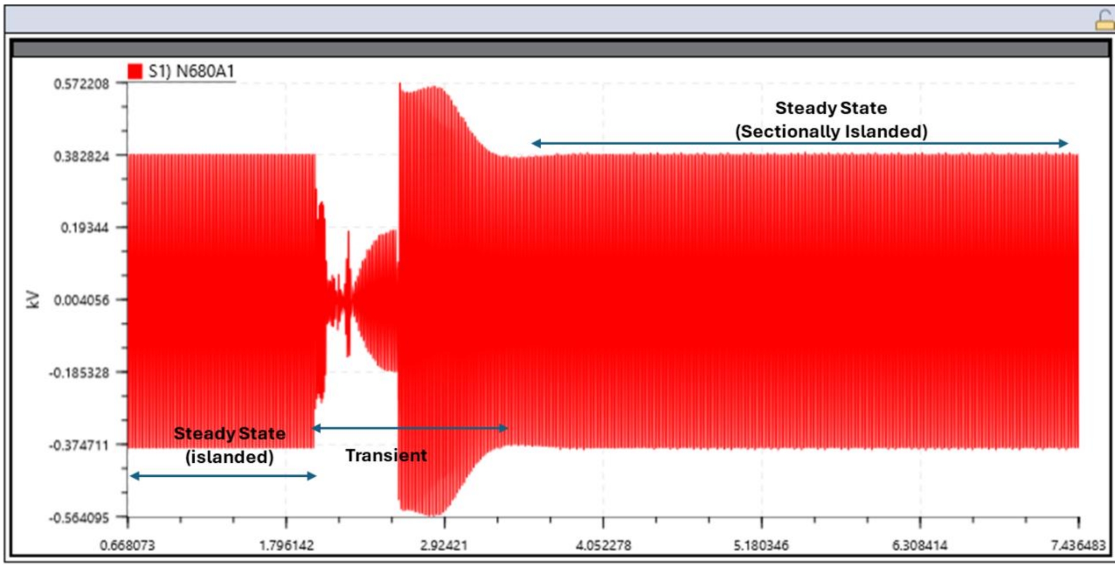


Figure 60: Transient behavior of bus voltage at sectional islanding

After this transition case 5 and 6 related to islanding case was implemented inside the bus 1, which showed similar results as the islanded case.

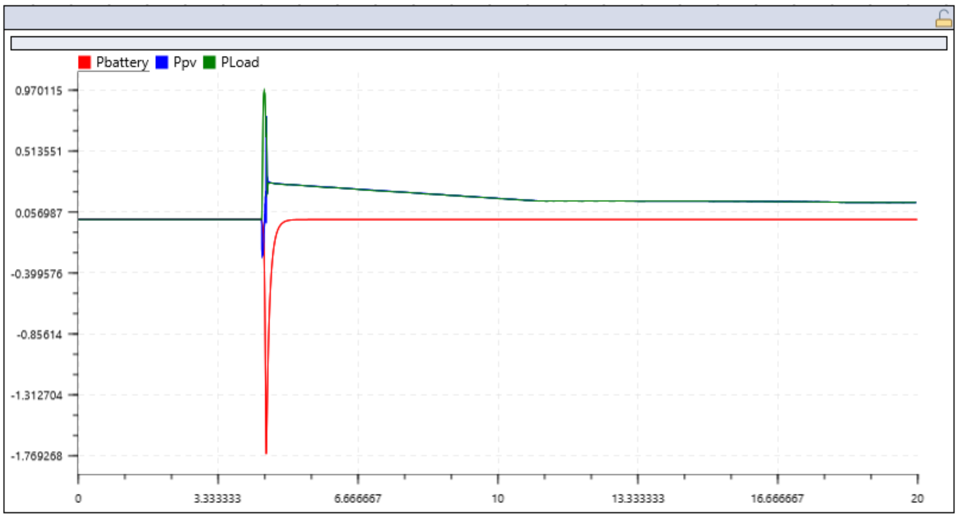


Figure 61: Example case implemented is islanded section (Irradiation=1000-400 W/m^2, Load=0.6 MW, SoC=20%)

According to above results of different operational modes, it can be claimed that following key points about this microgrid controller.

- In grid connected mode, the controller tends to cater load by excess solar generation, then charge the battery and at last export to the grid. On the other hand, the controller directs solar power totally to the load and then discharges the battery and then thinks of absorbing grid power, in case of low PV penetration.
- In islanded case, transition between modes is comparatively smooth due to the high inertia of the system. The controller mainly focusing on curtailing PV power at high PV penetrations and controlling loads at low PV penetrations, depending on the battery availability.
- In sectional islanding, the subjected sub distribution bus shows lower inertial, which results a high voltage transient as per the singulation, which leads to the stability, however. At the steady state, the system acts as a usually islanded system as per the overall system.

5. HARDWARE DEVELOPMENT

According to the scope of this research, UoM-LECO microgrid laboratory equipment is proposed to be integrated into single microgrid, according to the provided single line diagram in the simulation section. This builds a scaled-down microgrid system that implements similar operations in the simulated environment. This system contains the following equipment with detailed ratings. Rated voltage for all is 400V L-L.

Table 13: Lab Equipment Details

Equipment type	Containing Buses	Ratings
Solar PV inverter	1,2,3	Bus 1- 4kW Bus 2- 5kW Bus 3- 5kW
Battery Storage	1,2	Bus 1,2- 6kW
Loads	1,2,3	Bus 1,2,3- 1kW each

The proposed single line diagram and the total hardware architecture for the system is shown as follows.

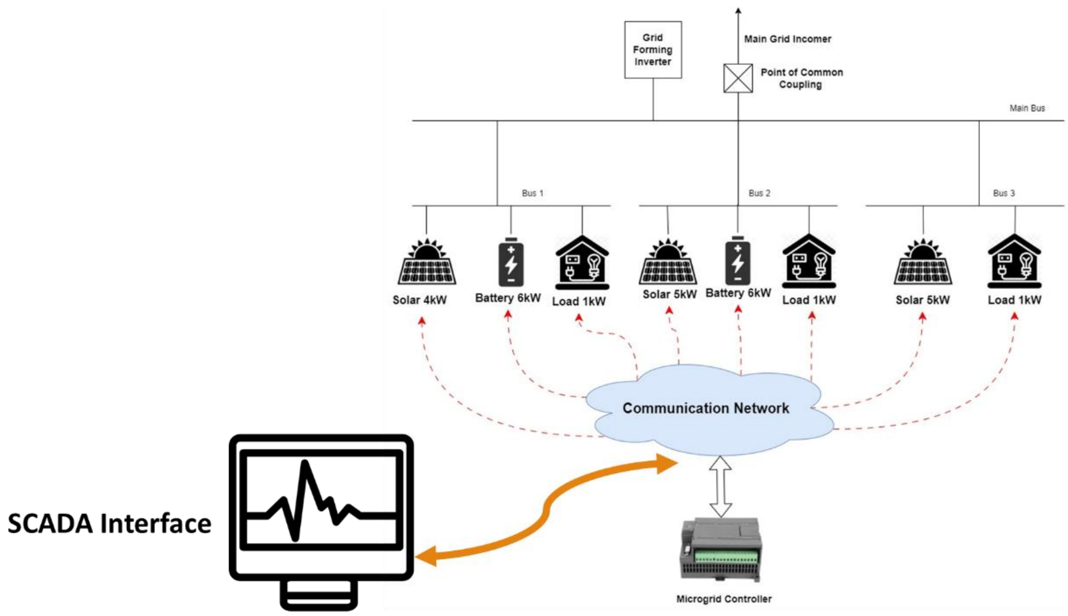


Figure 62: Proposed Hardware Architecture

5.1. New Additions for the System

To bring the system into the above platform, two major improvements were proposed.

1. Grid Forming Inverter Addition
2. Network Installation
3. AC and DC Wiring

5.1.1. Grid Forming Inverter (GFI) Addition

As mentioned in literature review, any microgrid system should have a DER that can provide voltage and frequency references to other DERs as the fixed voltage source inside the system. This DER is operated at a predefined droop setpoint and other DERs are following its voltage and frequency magnitudes, synchronized by PLLs inside their primary control layer. Victron MultiPlus II-GX single phase GFI was selected for the purpose.

The battery inverters that are included inside the laboratory are not capable of forming the grid because they were originally developed as grid following inverters. Under these circumstances, a separate GFI for grid forming purposes was proposed to be included. This GFI contains 3 single phase inverters, connected in Y configuration and their DC buses are connected to a 5kW 48V Li-Ion battery.

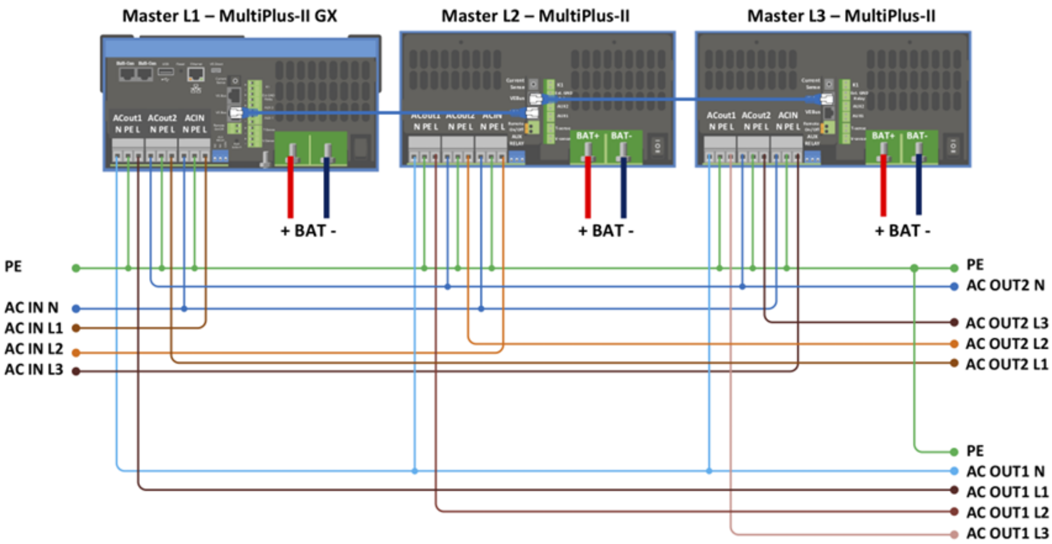


Figure 63: 3-phase connection of grid forming inverter.

Figure 64: 5kW Li-Ion Battery

The following table summarizes the grid forming inverter and battery specifications.

Table 14: GFI and battery Specifications

Grid Forming Inverter	Power rating for each– 5kW AC output Voltage- 230V L-N DC Bus Voltage- 48V DC Rated frequency- 50Hz Maximum AC input current-50A Maximum battery charging current- 70A
Li-Ion battery	Capacity- 100Ah Output voltage-48V DC Maximum Output Power- 5kW

5.1.2. Network Installation

To exchange data among DERs and controller, there should be a dedicated network connecting them together. As proposed, a dedicated TCP/IP network was installed in the lab environment containing dedicated Modbus-TCP port for each DER. Since each DER contains a dedicated ethernet port this installation is ideal to handle microgrid operation as intended.

First, a local area network is connected into a network switch through RJ45 network interfaces. This network is connected to a single network switch, setting up a local area network. The common protocol used in this network is Modbus TCP/IP.

(a) RJ45 Ports

(b) Network Switch

Figure 65: Network Installation Components

5.1.3. AC and DC Wiring

The new GFI installation required certain additions of AC and DC wiring to be fully functioning. This wiring contains a DC MCB and a busbar connection containing a DC distribution board and AC MCB with AC protection. Full wiring of the system is shown in appendix 1.

The completed installation is shown in figure 62.

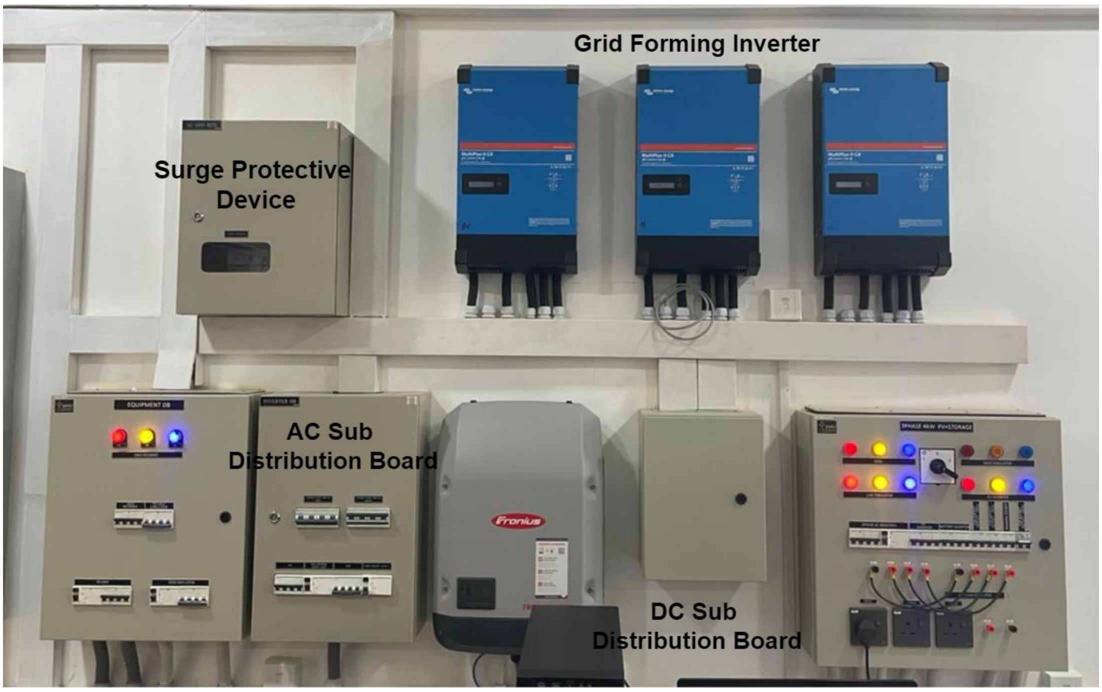


Figure 66: Completed Installation of GFI

Figure 63 contains a simplified version of new installation and exiting system, after development.

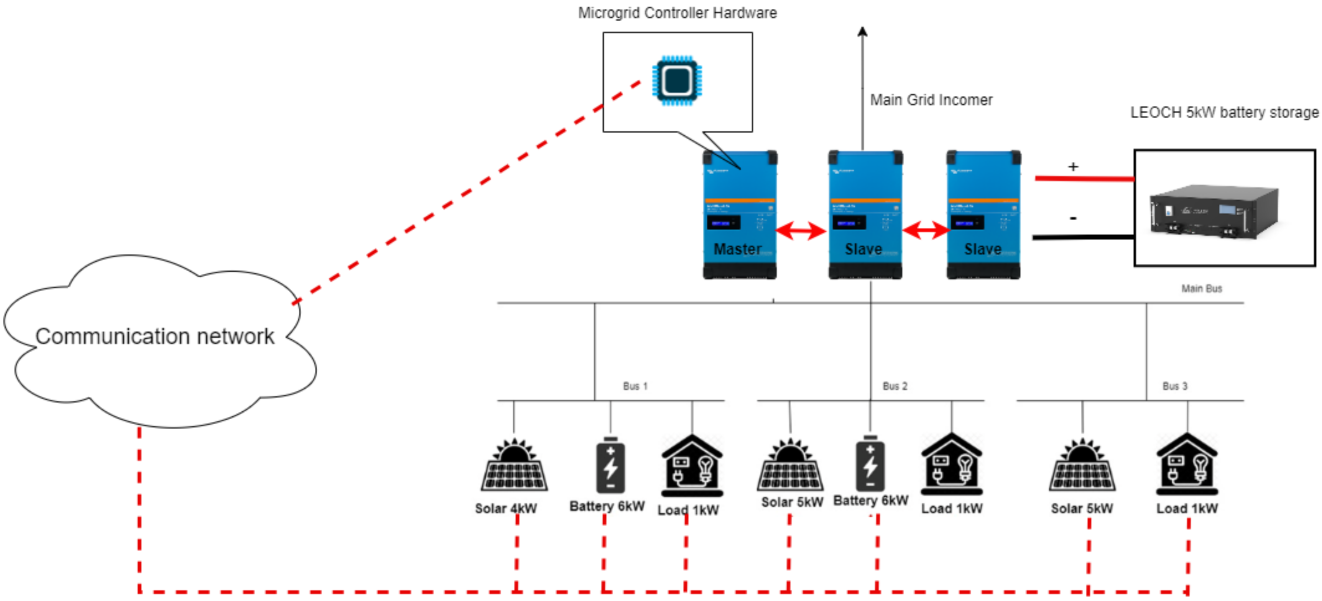


Figure 67: Overall System after development

5.2. System Operation Scenarios

Since this is a real system implemented inside a laboratory environment, there are certain limitations of the observations compared to the simulated system. Due to the inability of controlling solar irradiation given to the solar PV, system operation was recorded in different times complying with the simulated scenarios as follows. Operational scenarios were monitored by the built in web portal of the Victron Multiplus II-GX.

Figure 68: High loading, low PV scenario

In the above scenario, intermediate load is served by the GFI battery bank and PV generation, and small portion of the load is sent back to the grid.

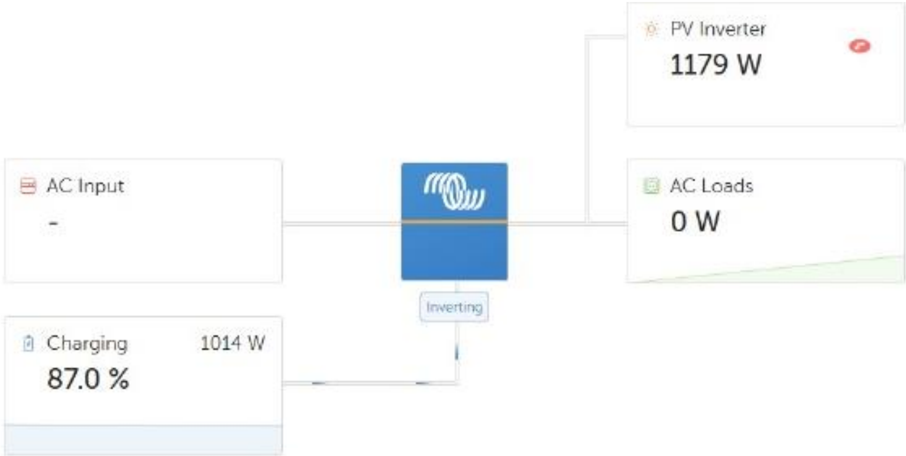


Figure 69: Islanded and loads are disconnected

In the afore scenario, total generation of PV is sent back to the GFI battery since no load is consumed inside the microgrid.

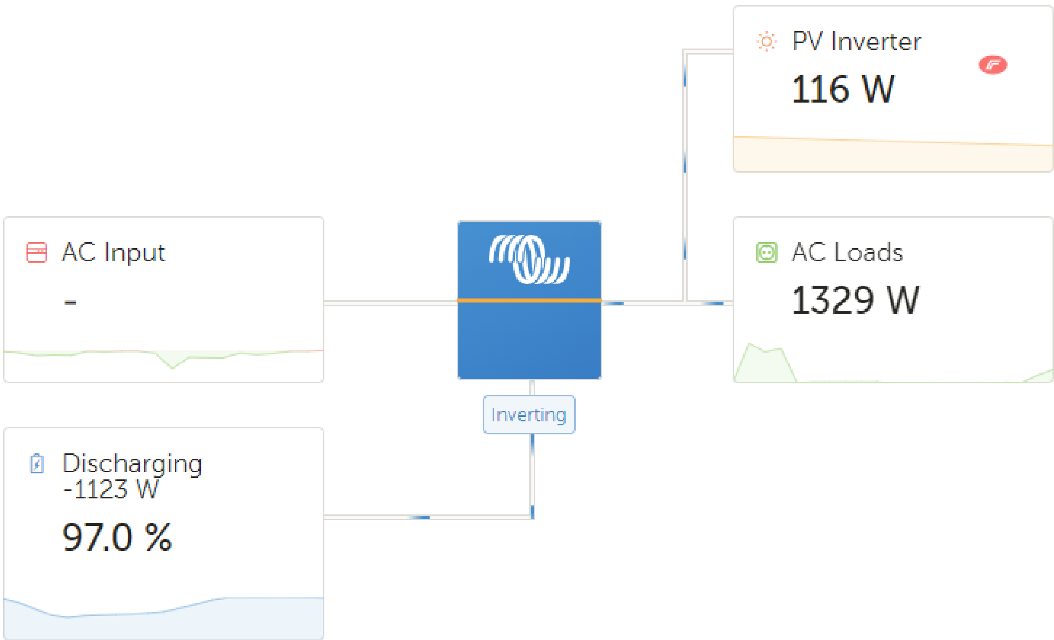


Figure 70: Islanded, low PV and loaded

In this scenario, battery bank has to be discharged to provide system load requirement accordingly. Note that this SCADA view does not depict the actual system built inside the laboratory. It only accounts for total solar power generation and load as a cumulative value and visualize the energy balance.

6. CONCLUSIONS AND FUTURE WORKS

Development of a sustainable and resilient microgrid controller for a certain application is a demanding characteristic inside a microgrid system, because these features directly ensure the reliability and economical independency of the microgrid, which seals the benefits for the consumers. Under this research, sustainability aspects of the microgrid were covered by enriching microgrid system only with solar PV, other than going for conventional energy resources. And inside the controller algorithm, certain strategies were implemented to ensure the PV generation is highly stored and used in the nighttime, which makes the microgrid operation more sustainable in energy management aspects as well. In terms of resiliency, a novel strategy of sectional islanding is proposed to continue the microgrid operation at internal distribution system faults. This strategy ensures the continuous supply of power to the loads even if the distribution system fails and cannot provide power from the external grid. Sub distribution buses are separately controlled to ensure the operation, independent form the distribution grid.

To meet the above requirements inside the grid, a central controller platform is proposed to be designed. This design contains two major developments: software simulation and hardware development. To design this a thorough literature review was done under controller architectures, control actions, sustainability improvement techniques and resiliency improvement techniques.

The simulation was done using real time simulation technology because its convenience of simulating electrical models al can be validated the system in real time updates. The use of real time digital simulations was super-fast compared to other simulation methods. These simulations were used to decide system behavior under different predefined conditions.

Hardware development was done by integrating a 3-phase GFI to the system and setting up a communication network for the system for the smooth control. Controlling hardware is nothing but the integrated controller inside the GFI, which can be programmed according to the desired controlling algorithm, which was proposed in chapter 3. A summary of objectives, methodology and how they have been addressed in the work is shown in table below.

Table 15: Summary of the work

Objectives	Methodology	Achievements
1. Develop a software-simulated microgrid controlling platform with relevant loads and source models	Performing a literature review on microgrid controlling	Completed the literature review under following themes • Controller architectures • Controller actions • Sustainability controls • Resilient controls
	Simulating a microgrid platform with collected data from the UOM-LECO research lab	Using RTDS and RSCAD to build up simulated microgrid system with controls
2. Integrating existing resources in the UOM-LECO microgrid lab into controlling platform hardware, to demonstrate sustainable and resilient energy management techniques with the required accuracy	Developing a microgrid controller laboratory set up in the laboratory environment with controlling strategies.	Addition of GFI and communication network Integrating control algorithm to the controller hardware
	Testing controller performance and validating with simulation results	Comparing operation with simulated results.

As future works, this control algorithm can be developed with optimization techniques to dispatch and control power generation efficiently.

7. REFERENCE

[1] A. Hussain, V. H. Bui, and H. M. Kim, “Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience,” *Applied Energy*, vol. 240. Elsevier Ltd, pp. 56–72, Apr. 15, 2019. doi: 10.1016/j.apenergy.2019.02.055.

[2] Y. Zahraoui *et al.*, “Energy management system in microgrids: A comprehensive review,” *Sustainability (Switzerland)*, vol. 13, no. 19, Oct. 2021, doi: 10.3390/su131910492.

[3] S. Chandak, B. Sahoo, P. K. Rout, S. Mishra, and M. Mishra, “A Brief Analysis on Microgrid Control,” in *Lecture Notes in Electrical Engineering*, Springer Science and Business Media Deutschland GmbH, 2022, pp. 541–553. doi: 10.1007/978-981-16-7076-3_46.

[4] *IEEE PC62.62/D3, November 2017 : IEEE Approved Draft Standard Test Specifications for Surge-Protective Devices (SPDs) for Use on the Load Side of the Service Equipment in Low-Voltage (1000 V and Less) AC Power Circuits.* IEEE, 2018.

[5] B. V. Solanki, K. Bhattacharya, and C. A. Canizares, “A Sustainable Energy Management System for Isolated Microgrids,” *IEEE Trans Sustain Energy*, vol. 8, no. 4, pp. 1507–1517, Oct. 2017, doi: 10.1109/TSTE.2017.2692754.

[6] H. A. Muqeet *et al.*, “Sustainable Solutions for Advanced Energy Management System of Campus Microgrids: Model Opportunities and Future Challenges,” *Sensors*, vol. 22, no. 6. MDPI, Mar. 01, 2022. doi: 10.3390/s22062345.

[7] A. Hussain, V. H. Bui, and H. M. Kim, “A Resilient and Privacy-Preserving Energy Management Strategy for Networked Microgrids,” *IEEE Trans Smart Grid*, vol. 9, no. 3, pp. 2127–2139, May 2018, doi: 10.1109/TSG.2016.2607422.

[8] A. Hussain, A. Oulis Rousis, I. Konstantelos, G. Strbac, J. Jeon, and H. M. Kim, “Impact of Uncertainties on Resilient Operation of Microgrids: A Data-Driven Approach,” *IEEE Access*, vol. 7, pp. 4924–14937, 2019, doi: 10.1109/ACCESS.2019.2891786.

[9] A. Choudar, D. Boukhetala, S. Barkat, and J. M. Brucker, "A local energy management of a hybrid PV-storage based distributed generation for microgrids," *Energy Convers Manag*, vol. 90, pp. 21–33, Jan. 2015, doi: 10.1016/j.enconman.2014.10.067.

[10] M. Mathew, M. S. Hossain, S. Saha, S. Mondal, and M. E. Haque, "Sizing approaches for solar photovoltaic-based microgrids: A comprehensive review," *IET Energy Systems Integration*, vol. 4, no. 1. John Wiley and Sons Inc, pp. 1–27, Mar. 01, 2022. doi: 10.1049/esi2.12048.

[11] Y. E. G. Vera, R. Dufo-López, and J. L. Bernal-Agustín, "Energy management in microgrids with renewable energy sources: A literature review," *Applied Sciences (Switzerland)*, vol. 9, no. 18. MDPI AG, Sep. 01, 2019. doi: 10.3390/app9183854.

[12] M. A. Khan, A. Haque, and V. S. Bharath Kurukuru, "Reliability analysis of a solar inverter during reactive power injection," in *9th IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2020*, Institute of Electrical and Electronics Engineers Inc., Dec. 2020. doi: 10.1109/PEDES49360.2020.9379776.

[13] M. Ramesh, A. K. Yadav, and P. K. Pathak, "An extensive review on load frequency control of solar-wind based hybrid renewable energy systems," *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. Bellwether Publishing, Ltd., 2021. doi: 10.1080/15567036.2021.1931564.

[14] G. M. Joselin Herbert, S. Iniyan, E. Sreevalsan, and S. Rajapandian, "A review of wind energy technologies," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 6. pp. 1117–1145, Aug. 2007. doi: 10.1016/j.rser.2005.08.004.

[15] Z. Cui, L. Song, and S. Li, "Maximum Power Point Tracking Strategy for a New Wind Power System and Its Design Details," *IEEE Transactions on Energy Conversion*, vol. 32, no. 3, pp. 1063–1071, Sep. 2017, doi: 10.1109/TEC.2017.2694008.

[16] W. Gil-González, O. D. Montoya, and A. Garces, "Modeling and control of a small hydro-power plant for a DC microgrid," *Electric Power Systems Research*, vol. 180, Mar. 2020, doi: 10.1016/j.epsr.2019.106104.

[17] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, “An Overview of Ongoing Research, Development, and Demonstration Projects.” [Online]. Available: http://ec.europa.eu/research/energy/pdf/smartgrids_

[18] Z. Zhang, X. Yang, Z. Wang, Z. Chen, and Y. Zheng, “Highly applicable small hydropower microgrid operation strategy and control technology,” *Energy Reports*, vol. 6, pp. 3179–3191, Nov. 2020, doi: 10.1016/j.egyr.2020.08.037.

[19] J. P. Barton and D. G. Infield, “Energy storage and its use with intermittent renewable energy,” *IEEE Transactions on Energy Conversion*, vol. 19, no. 2, pp. 441–448, Jun. 2004, doi: 10.1109/TEC.2003.822305.

[20] K. Balasubramaniam, P. Saraf, R. Hadidi, and E. B. Makram, “Energy management system for enhanced resiliency of microgrids during islanded operation,” *Electric Power Systems Research*, vol. 137, pp. 133–141, Aug. 2016, doi: 10.1016/j.epsr.2016.04.006.

[21] M. F. Zia, E. Elbouchikhi, and M. Benbouzid, “Microgrids energy management systems: A critical review on methods, solutions, and prospects,” *Applied Energy*, vol. 222. Elsevier Ltd, pp. 1033–1055, Jul. 15, 2018. doi: 10.1016/j.apenergy.2018.04.103.

[22] M. R. Aghamohammadi and H. Abdolahinia, “A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid,” *International Journal of Electrical Power and Energy Systems*, vol. 54, pp. 325–333, 2014, doi: 10.1016/j.ijepes.2013.07.005.

[23] K. C. Divya and J. Østergaard, “Battery energy storage technology for power systems-An overview,” *Electric Power Systems Research*, vol. 79, no. 4. pp. 511–520, Apr. 2009. doi: 10.1016/j.epsr.2008.09.017.

[24] C. Chen, J. Wang, F. Qiu, and D. Zhao, “Resilient Distribution System by Microgrids Formation after Natural Disasters,” *IEEE Trans Smart Grid*, vol. 7, no. 2, pp. 958–966, Mar. 2016, doi: 10.1109/TSG.2015.2429653.

[25] M. Simonov, “Dynamic partitioning of DC microgrid in resilient clusters using event-driven approach,” *IEEE Trans Smart Grid*, vol. 5, no. 5, pp. 2618–2625, Sep. 2014, doi: 10.1109/TSG.2014.2302992.

[26] M. Zadsar, M. R. Haghifam, and S. M. M. Larimi, "Approach for self-healing resilient operation of active distribution network with microgrid," *IET Generation, Transmission and Distribution*, vol. 11, no. 18, pp. 4633–4643, Dec. 2017, doi: 10.1049/iet-gtd.2016.1783.

[27] A. Hussain, V. H. Bui, and H. M. Kim, "Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience," *Applied Energy*, vol. 240. Elsevier Ltd, pp. 56–72, Apr. 15, 2019. doi: 10.1016/j.apenergy.2019.02.055.

[28] Zaheeruddin and M. Manas, "Renewable energy management through microgrid central controller design: An approach to integrate solar, wind and biomass with battery," *Energy Reports*, vol. 1, pp. 156–163, Jul. 2015, doi: 10.1016/j.egyr.2015.06.003.

[29] "Control of Hybrid ACDC Microgrid Involving Energy".

[30] G. Shahgholian, "A brief review on microgrids: Operation, applications, modeling, and control," *International Transactions on Electrical Energy Systems*, vol. 31, no. 6. John Wiley and Sons Ltd, Jun. 01, 2021. doi: 10.1002/2050-7038.12885.

[31] J. J. Justo, F. Mwasilu, J. Lee, and J. W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews*, vol. 24. pp. 387–405, 2013. doi: 10.1016/j.rser.2013.03.067.

[32] X. Wang, J. M. Guerrero, F. Blaabjerg, and Z. Chen, "A review of power electronics based microgrids," *Journal of Power Electronics*, vol. 12, no. 1, pp. 181–192, Jan. 2012, doi: 10.6113/JPE.2012.12.1.181.

[33] L. Ortiz, R. Orizondo, A. Águila, J. W. González, G. J. López, and I. Isaac, "Hybrid AC/DC microgrid test system simulation: grid-connected mode," *Heliyon*, vol. 5, no. 12, Dec. 2019, doi: 10.1016/j.heliyon.2019.e02862.

[34] L. Ahmethodzic and M. Music, "Comprehensive review of trends in microgrid control," *Renewable Energy Focus*, vol. 38. Elsevier Ltd, pp. 84–96, Sep. 01, 2021. doi: 10.1016/j.ref.2021.07.003.

[35] O. Abrishambaf, P. Faria, L. Gomes, J. Spínola, Z. Vale, and J. M. Corchado, "Implementation of a real-time microgrid simulation platform based on centralized and distributed management," *Energies (Basel)*, vol. 10, no. 6, Jun. 2017, doi: 10.3390/en10060806.

[36] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," *IEEE Trans Smart Grid*, vol. 3, no. 4, pp. 1963–1976, 2012, doi: 10.1109/TSG.2012.2197425.

[37] S. Ishaq, I. Khan, S. Rahman, T. Hussain, A. Iqbal, and R. M. Elavarasan, "A review on recent developments in control and optimization of micro grids," *Energy Reports*, vol. 8. Elsevier Ltd, pp. 4085–4103, Nov. 01, 2022. doi: 10.1016/j.egyr.2022.01.080.

[38] H. Liang, B. J. Choi, W. Zhuang, and X. Shen, "Stability enhancement of decentralized inverter control through wireless communications in microgrids," *IEEE Trans Smart Grid*, vol. 4, no. 1, pp. 321–331, 2013, doi: 10.1109/TSG.2012.2226064.

[39] M. H. Cintuglu, T. Youssef, and O. A. Mohammed, "Development and application of a real-time testbed for multiagent system interoperability: A case study on hierarchical microgrid control," *IEEE Trans Smart Grid*, vol. 9, no. 3, pp. 1759–1768, May 2018, doi: 10.1109/TSG.2016.2599265.

[40] S. A. P. Kani, F. Shahnia, M. I. Azim, M. A. Shoeb, and G. M. Shafiullah, "Microgrid control overview," in *Variability, Scalability and Stability of Microgrids*, Institution of Engineering and Technology, 2019, pp. 15–71. doi: 10.1049/pbpo139e_ch2.

[41] B. J. Brearley and R. R. Prabu, "A review on issues and approaches for microgrid protection," *Renewable and Sustainable Energy Reviews*, vol. 67. Elsevier Ltd, pp. 988–997, Jan. 01, 2017. doi: 10.1016/j.rser.2016.09.047.

[42] J. A. P. Lopes, C. L. Moreira, and A. G. Madureira, "Defining control strategies for microgrids islanded operation," *IEEE Transactions on Power Systems*, vol. 21, no. 2, pp. 916–924, May 2006, doi: 10.1109/TPWRS.2006.873018.

[43] H. Laaksonen, D. Ishchenko, and A. Oudalov, "Adaptive protection and microgrid control design for Hailuoto Island," *IEEE Trans Smart Grid*, vol. 5, no. 3, pp. 1486–1493, 2014, doi: 10.1109/TSG.2013.2287672.

[44] W. Du *et al.*, "Modeling of Grid-Forming and Grid-Following Inverters for Dynamic Simulation of Large-Scale Distribution Systems," *IEEE Transactions on Power Delivery*, vol. 36, no. 4, pp. 2035–2045, Aug. 2021, doi: 10.1109/TPWRD.2020.3018647.

[45] Y. Zuo, Z. Yuan, F. Sossan, A. Zecchino, R. Cherkaoui, and M. Paolone, "Performance assessment of grid-forming and grid-following converter-interfaced battery energy storage systems on frequency regulation in low-inertia power grids," *Sustainable Energy, Grids and Networks*, vol. 27, Sep. 2021, doi: 10.1016/j.segan.2021.100496.

[46] E. Rokrok, M. Shafie-khah, and J. P. S. Catalão, "Review of primary voltage and frequency control methods for inverter-based islanded microgrids with distributed generation," *Renewable and Sustainable Energy Reviews*, vol. 82. Elsevier Ltd, pp. 3225–3235, Feb. 01, 2018. doi: 10.1016/j.rser.2017.10.022.

[47] Y. A. R. I. Mohamed and E. F. El-Saadany, "Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids," *IEEE Trans Power Electron*, vol. 23, no. 6, pp. 2806–2816, 2008, doi: 10.1109/TPEL.2008.2005100.

[48] J. M. Guerrero, L. García de Vicuña, J. Matas, M. Castilla, and J. Miret, "Output impedance design of parallel-connected UPS inverters with wireless load-sharing control," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 4, pp. 1126–1135, Aug. 2005, doi: 10.1109/TIE.2005.851634.

[49] Z. Luo, Z. Wu, Z. Li, H. Y. Cai, B. J. Li, and W. Gu, "A two-stage optimization and control for CCHP microgrid energy management," *Appl Therm Eng*, vol. 125, pp. 513–522, 2017, doi: 10.1016/j.applthermaleng.2017.05.188.

[50] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Stochastic Energy Management of Microgrids during Unscheduled Islanding Period," *IEEE Trans Industr Inform*, vol. 13, no. 3, pp. 1079–1087, Jun. 2017, doi: 10.1109/TII.2016.2646721.

[51] C. Chen, S. Duan, T. Cai, B. Liu, and G. Hu, "Smart energy management system for optimal microgrid economic operation," *IET Renewable Power Generation*, vol. 5, no. 3, pp. 258–267, May 2011, doi: 10.1049/iet-rpg.2010.0052.

[52] J. P. Fossati, A. Galarza, A. Martín-Villate, J. M. Echeverría, and L. Fontán, "Optimal scheduling of a microgrid with a fuzzy logic controlled storage system," *International Journal of Electrical Power and Energy Systems*, vol. 68, pp. 61–70, 2015, doi: 10.1016/j.ijepes.2014.12.032.

[53] S. A. Alavi, A. Ahmadian, and M. Aliakbar-Golkar, "Optimal probabilistic energy management in a typical micro-grid based-on robust optimization and point estimate method," *Energy Convers Manag*, vol. 95, pp. 314–325, May 2015, doi: 10.1016/j.enconman.2015.02.042.

[54] M. Sechilariu, B. Wang, and F. Locment, "Building-integrated microgrid: Advanced local energy management for forthcoming smart power grid communication," *Energy Build*, vol. 59, pp. 236–243, 2013, doi: 10.1016/j.enbuild.2012.12.039.

[55] B. Heymann, J. F. Bonnans, P. Martinon, F. J. Silva, F. Lanas, and G. Jiménez-Estévez, "Continuous optimal control approaches to microgrid energy management," *Energy Systems*, vol. 9, no. 1, pp. 59–77, Feb. 2018, doi: 10.1007/s12667-016-0228-2.

[56] A. L. Bukar, C. W. Tan, L. K. Yiew, R. Ayop, and W. S. Tan, "A rule-based energy management scheme for long-term optimal capacity planning of grid-independent microgrid optimized by multi-objective grasshopper optimization algorithm," *Energy Convers Manag*, vol. 221, Oct. 2020, doi: 10.1016/j.enconman.2020.113161.

[57] V. S. B. Kurukuru, A. Haque, S. Padmanaban, and M. A. Khan, "Rule-Based Inferential System for Microgrid Energy Management System," *IEEE Syst J*, vol. 16, no. 1, pp. 1582–1591, Mar. 2022, doi: 10.1109/JSYST.2021.3094403.

[58] T. Pippia, J. Sijs, and B. De Schutter, "A Single-Level Rule-Based Model Predictive Control Approach for Energy Management of Grid-Connected Microgrids," *IEEE Transactions on Control Systems Technology*, vol. 28, no. 6, pp. 2364–2376, Nov. 2020, doi: 10.1109/TCST.2019.2945023.

[59] F. Garcia-Torres and C. Bordons, "Optimal Economical Schedule of Hydrogen-Based Microgrids With Hybrid Storage Using Model Predictive Control," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 8, pp. 5195–5207, Aug. 2015, doi: 10.1109/TIE.2015.2412524.

[60] B. Lu and M. Shahidehpour, "Short-term scheduling of battery in a grid-connected PV/battery system," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 1053–1061, May 2005, doi: 10.1109/TPWRS.2005.846060.

[61] A. C. Luna, N. L. Diaz, M. Graells, J. C. Vasquez, and J. M. Guerrero, "Mixed-integer-linear-programming-based energy management system for hybrid PV-wind-battery microgrids: Modeling, design, and experimental verification," *IEEE Trans Power Electron*, vol. 32, no. 4, pp. 2769–2783, Apr. 2017, doi: 10.1109/TPEL.2016.2581021.

[62] M. Marzband, F. Azarinejadian, M. Savaghebi, and J. M. Guerrero, "An optimal energy management system for islanded microgrids based on multiperiod artificial bee colony combined with markov chain," *IEEE Syst J*, vol. 11, no. 3, pp. 1712–1722, Sep. 2017, doi: 10.1109/JSYST.2015.2422253.

[63] J. T. Yu, C. H. Kim, A. Wadood, T. Khurshaid, and S. B. Rhee, "Jaya Algorithm with Self-Adaptive Multi-Population and Lévy Flights for Solving Economic Load Dispatch Problems," *IEEE Access*, vol. 7, pp. 21372–21384, 2019, doi: 10.1109/ACCESS.2019.2899043.

[64] Y. Cao *et al.*, "An optimized EV charging model considering TOU price and SOC curve," *IEEE Trans Smart Grid*, vol. 3, no. 1, pp. 388–393, Mar. 2012, doi: 10.1109/TSG.2011.2159630.

[65] M. S. Taha, H. H. Abdeltawab, and Y. A. R. I. Mohamed, "An online energy management system for a grid-connected hybrid energy source," *IEEE J Emerg Sel Top Power Electron*, vol. 6, no. 4, pp. 2015–2030, Dec. 2018, doi: 10.1109/JESTPE.2018.2828803.

[66] Z. Wang, X. Song, H. Xin, D. Gan, and K. P. Wong, "Risk-based coordination of generation rescheduling and load shedding for transient stability enhancement," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4674–4682, 2013, doi: 10.1109/TPWRS.2013.2262719.

[67] M. Elsied, A. Oukaour, T. Youssef, H. Gualous, and O. Mohammed, “An advanced real time energy management system for microgrids,” *Energy*, vol. 114, pp. 742–752, Nov. 2016, doi: 10.1016/j.energy.2016.08.048.

[68] D. E. Olivares, C. A. Canizares, and M. Kazerani, “A centralized energy management system for isolated microgrids,” *IEEE Trans Smart Grid*, vol. 5, no. 4, pp. 1864–1875, 2014, doi: 10.1109/TSG.2013.2294187.

[69] J. Tobajas, F. Garcia-Torres, P. Roncero-Sánchez, J. Vázquez, L. Bellatreche, and E. Nieto, “Resilience-oriented schedule of microgrids with hybrid energy storage system using model predictive control,” *Appl Energy*, vol. 306, p. 118092, Jan. 2022, doi: 10.1016/j.apenergy.2021.118092.

[70] M. Uzair, L. Li, J. G. Zhu, and M. Eskandari, “A protection scheme for AC microgrids based on multi-agent system combined with machine learning,” in *2019 29th Australasian Universities Power Engineering Conference, AUPEC 2019*, Institute of Electrical and Electronics Engineers Inc., Nov. 2019. doi: 10.1109/AUPEC48547.2019.211845.

[71] S. Marzal, R. Salas, R. González-Medina, G. Garcerá, and E. Figueres, “Current challenges and future trends in the field of communication architectures for microgrids,” *Renewable and Sustainable Energy Reviews*, vol. 82. Elsevier Ltd, pp. 3610–3622, Feb. 01, 2018. doi: 10.1016/j.rser.2017.10.101.

[72] M. Rice and S. Shenoi, Eds., *Critical Infrastructure Protection IX*, vol. 466. in IFIP Advances in Information and Communication Technology, vol. 466. Cham: Springer International Publishing, 2015. doi: 10.1007/978-3-319-26567-4.

[73] D. Jin *et al.*, “Toward a Cyber Resilient and Secure Microgrid Using Software-Defined Networking,” *IEEE Trans Smart Grid*, vol. 8, no. 5, pp. 2494–2504, Sep. 2017, doi: 10.1109/TSG.2017.2703911.

[74] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, “Networked Microgrids for Enhancing the Power System Resilience,” *Proceedings of the IEEE*, vol. 105, no. 7. Institute of Electrical and Electronics Engineers Inc., pp. 1289–1310, Jul. 01, 2017. doi: 10.1109/JPROC.2017.2685558.

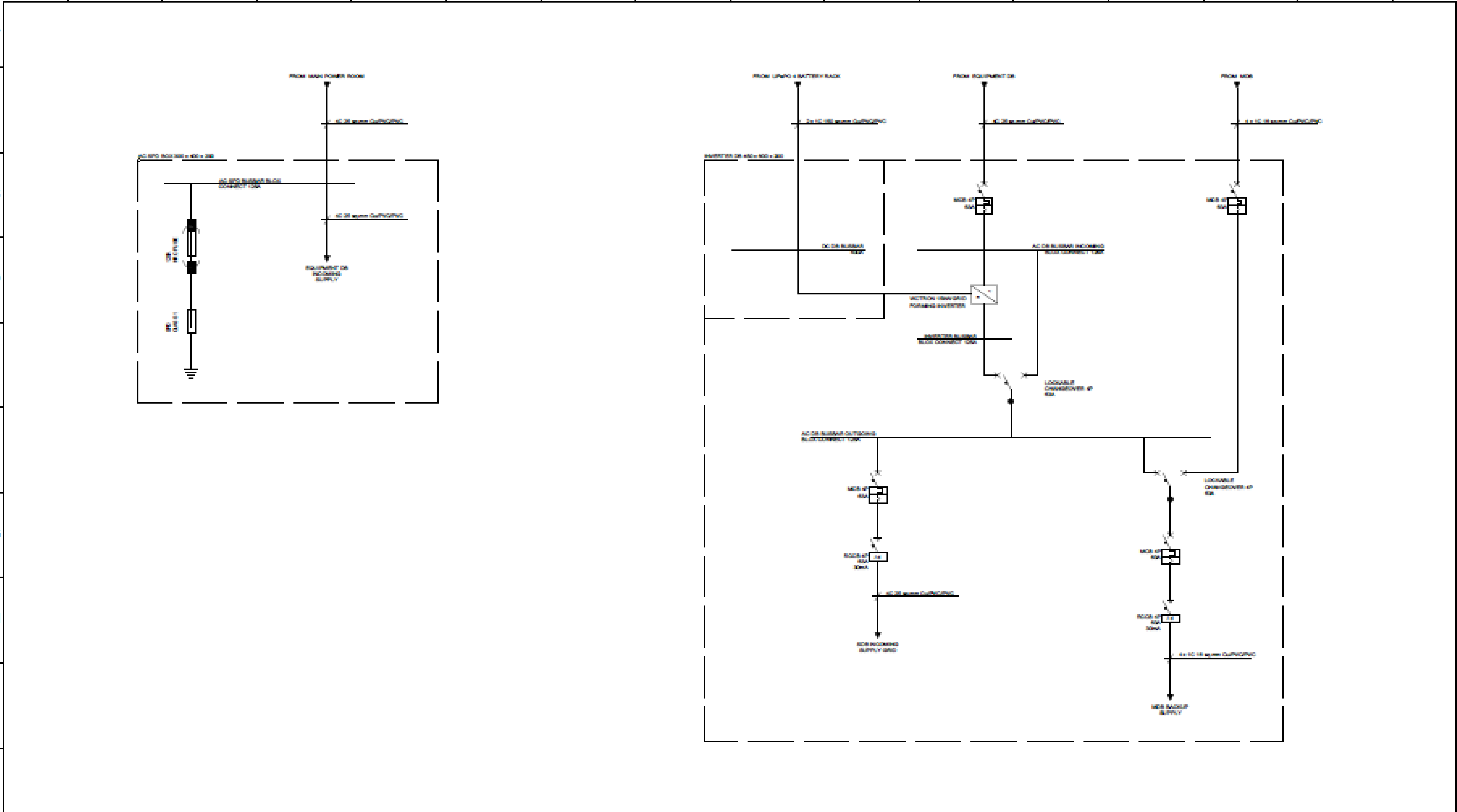
[75] R. Hemmati, H. Mehrjerdi, and S. M. Nosratabadi, “Resilience-oriented adaptable microgrid formation in integrated electricity-gas system with deployment of multiple energy hubs,” *Sustain Cities Soc*, vol. 71, Aug. 2021, doi: 10.1016/j.scs.2021.102946.

[76] M. H. Amirioun, F. Aminifar, and H. Lesani, “Towards Proactive Scheduling of Microgrids Against Extreme Floods,” *IEEE Trans Smart Grid*, vol. 9, no. 4, pp. 3900–3902, Jul. 2018, doi: 10.1109/TSG.2017.2762906.

[77] A. Anurag, Y. Yang, and F. Blaabjerg, “Thermal Performance and Reliability Analysis of Single-Phase PV Inverters with Reactive Power Injection Outside Feed-In Operating Hours,” *IEEE J Emerg Sel Top Power Electron*, vol. 3, no. 4, pp. 870–880, Dec. 2015, doi: 10.1109/JESTPE.2015.2428432.

[78] M. Chen and G. A. Rincón-Mora, “Accurate electrical battery model capable of predicting runtime and I-V performance,” *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 504–511, Jun. 2006, doi: 10.1109/TEC.2006.874229.

Appendix 1: Single Line Diagram of Installed Distribution Board



RENOVATION AND EXTENSION OF THE SMART GRID LABORATORY SLD GRID FORMING INVERTER SETUP	CREATED BY		REV. NO.	DATE	DESCRIPTION	DESCRIPTION	
	DESIGNED BY	Eng. W H Eranga	0	14.03.2024			
	CHECKED BY	Prof. K T M U Hemapala	1	26.03.2024		SHEET NO	1
	DRAWN BY	Eng. W H Eranga				NO OF SHEETS	1
	APPROVED BY					SCALE	: