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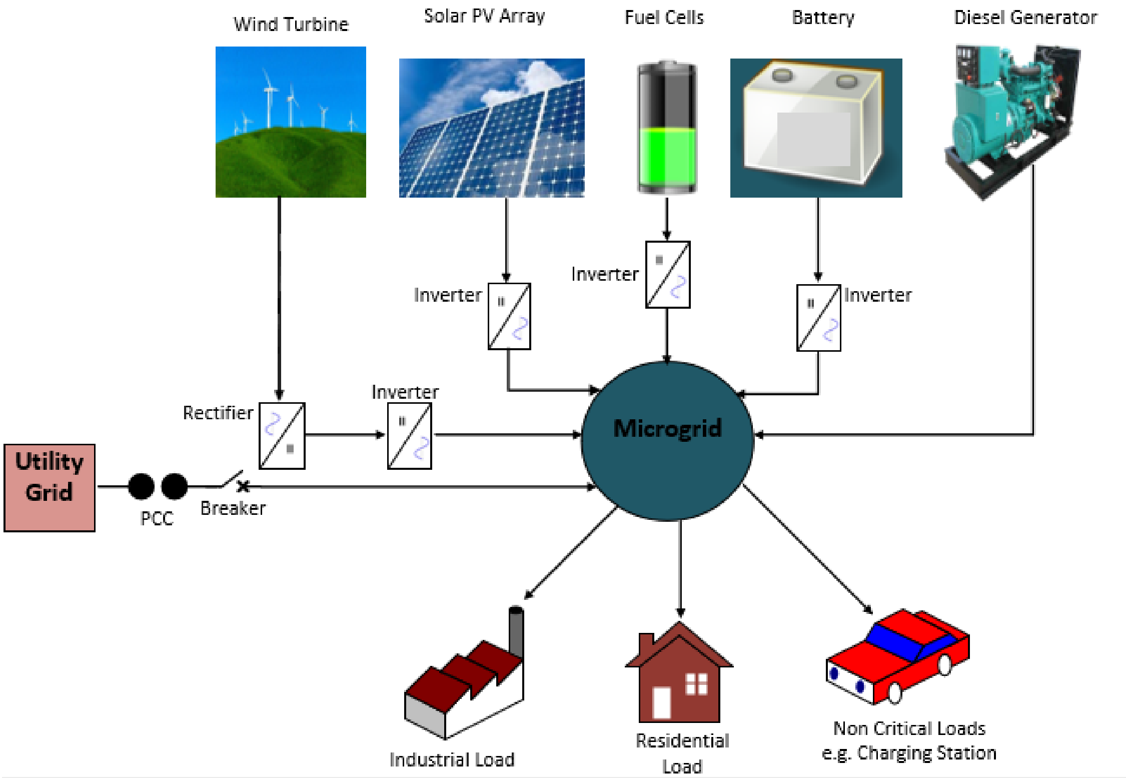

Modelling of Converters Dominated AC Microgrid with Communication System

Master's thesis in Electric Power Engineering

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Department of Electrical Engineering
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Abstract

Due to the ever increasing demand of electricity to fulfill our energy requirements and achieving CO_2 reduction goals at the same time, microgrids with renewable energy sources are playing vital role. A microgrid is a small scale power system with its own energy resources with the ability to supply the consumers even in case of contingencies at the main grid. Modern microgrids integrate renewable sources, which are typically interfaced through power electronic converters. These converters are coordinated through a communication system.

For this thesis, a microgrid model with a solar PV unit and a battery energy storage system(BESS) has been implemented with a centralized controller using PSCAD. Local controllers for both solar PV unit and battery unit have been designed for the case of islanded mode operation. There is also a secondary controller, called central controller, which regulates the battery power and solar power in case of islanded mode to keep balance between the generation and load. For controlling the power in the grid connected mode, utility grid power controller has been implemented as per the requirement of the microgrid to be operated in power control mode when operating in grid connected mode. In islanded mode, battery controller is the one which controls the voltages of the microgrids and, thus, system works in voltage control mode. Finally the impacts of communication delay on the converters coordination, and eventually the system behaviour, have been investigated.

Maximum rating of solar PV unit, battery unit and load are 100 kW, 210 Ahr and 68 kW respectively while system operates at nominal voltage and frequency values of 400 V and 50 Hz respectively. It has been found that communication delays in transition from grid connected mode to islanded mode can cause instability if they exceed certain value. Moreover, it has been found that system is able to survive with long delays between the controllers if the generation is close to the demand. Finally the comparison of the power outputs from the converters has been presented with different communication time delays and operating parameters.

Keywords: Microgrid, Power Electronic Converters, Wireless Communication, Battery Energy Storage System, Photovoltaic Array

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Muhammad Ahsan Kabir, Gothenburg, February 2019

Contents

List of Figures

List of Tables

1
Introduction

1.1 Background and Motivation

Micro-grids can be defined as small scale power system that are able to supply power to electricity consumers even if disconnected from the main system. It is a concept where distributed energy resources are preferred over the centralized conventional power systems. Due to high power demand in modern world and the goal of decreasing CO_2 emissions worldwide, renewable energy sources (RES) are increasingly gaining attention as an alternative to reach the CO_2 emissions' goal. However, along with the benefits, RES bring in also challenges, being the most recognized variable power sources. Typically, in a micro-grid, this is overcome through coordination between different resources such as energy storage and other flexible energy sources[1].

Distributed energy resources includes energy production from sources such as solar cells, fuel cells, wind power, energy storage devices (e.g. batteries), small CHP and diesel generators. In this regard, converters have a major role when we talk about these small scale power systems since they allow the connection of dc-voltage based energy sources to 50 Hz or 60 Hz ac systems and also are used to convert any other frequency value to nominal one e.g. in case of wind[2].

As mentioned above, one shortcoming of RES is their variability. One way to overcome this problem is through the coordination of the resources in the microgrid, which involves the need for communication. Due to the variability of RES, it is essential to have a communication system to coordinate the resources in a microgrid such that production and consumption is in balance. A good communication system in the micro-grid facilitates avoiding interruptions in the supply of power even if one source is not producing enough energy to meet the requirement.

1.2 Problem Statement and Aim

The objective of this thesis work is to study the impact on the dynamic performance of microgrid when a number converters are operating and coordinating together through a communication system in the microgrid. In this regard, it is important to consider the impact of events such as delays in the communication on the system performance.

1.3 Methodology

To analyze the dynamic behaviour of a power electronic converters dominated microgrid, a model of the AC microgrid with solar PV and Battery Energy Storage System (BESS) as RES will be implemented. The behaviour of the microgrid for both grid connected and isolated modes will be studied. The model will be implemented in an Electromagnetic Transient (EMT)/PSCAD program and the impact of communication delays between the devices in the grid will be investigated with the help of implemented model. Findings of the work and recommendations for the future work will be presented in the thesis.

1.4 Scope

A microgrid consists of different energy source. However, for the thesis work only solar PV and battery will be considered. Modelling of the battery unit and solar PV unit will be described along with the inverter topologies for the thesis and the converters are modelled as average models only. Control strategies of the local controllers of solar PV unit and battery unit will be implemented. Central controller for the regulation of battery power will be designed as a master controller to command the local controllers. The design of communication network is beyond the scope of the thesis and delays are only considered in this thesis. Also protection system of a microgrid is not included in the scope of this thesis. The study deals with the fast dynamics thus optimal operating points are not considered in the thesis.

1.5 Contribution

A microgrid model has been implemented with only solar PV and battery as energy sources. Control strategies for islanded operation mode have been implemented and system behaviour has been analyzed. After modelling the microgrid, communication delays have been introduced for different cases e.g. delay in transition feedback and the delay in solar PV controller etc. The behaviour of the system has been investigated due to these delays. Delays with different operating parameters e.g solar irradiance and connected load etc. has been observed and a comparative analysis has been presented. The thesis also shows the point where the system is most likely to able to survive even if there is some disturbance in communication delay or operating parameters.

1.6 Thesis Outline

Chapters are summarized below excluding the introduction chapter.

- Chapter 2 describes the importance of microgrid alongwith its components and challenges.
- Chapter 3 provides the modelling of components used to model the system for the thesis work.
- Chapter 4 shows the controllers implementation which have been designed to model the microgrid.
- Chapter 5 is related to communication systems which are used in the microgrids in modern days.
- Chapter 6 presents the simulation results of the work and performs the corresponding analysis.
- Chapter 7 presents concluding remarks for the thesis and also suggestions for the future work.

2

Importance of Microgrid and its Components

2.1 Energy Sources in Microgrids

A microgrid refers to the network of distributed energy sources and loads that can be operated in a coordinated way. It can integrate both conventional and renewable energy sources. Due to the goals of decreasing CO_2 emissions worldwide, renewable energy sources are gaining attention as an alternative to conventional sources for achieving the goal of reduction in carbon footprints while fulfilling our energy demands. Typical sources which are included in the micro grid are solar PVs, wind turbines, hydrogen fuel cells, small hydro, small combined heat and power (CHP) plant.

Apart from these energy generating sources, energy storage plays a key role in the successful operation of a microgrid. Batteries with proper control of power can be used to store energy when there is excess of energy, e.g power produced by a solar PV. When there is a deficit of power from renewable sources, this stored energy can be utilized to provide the uninterrupted power to the consumers. Other energy storage devices that can be mentioned are super-capacitors and flywheels, for example.

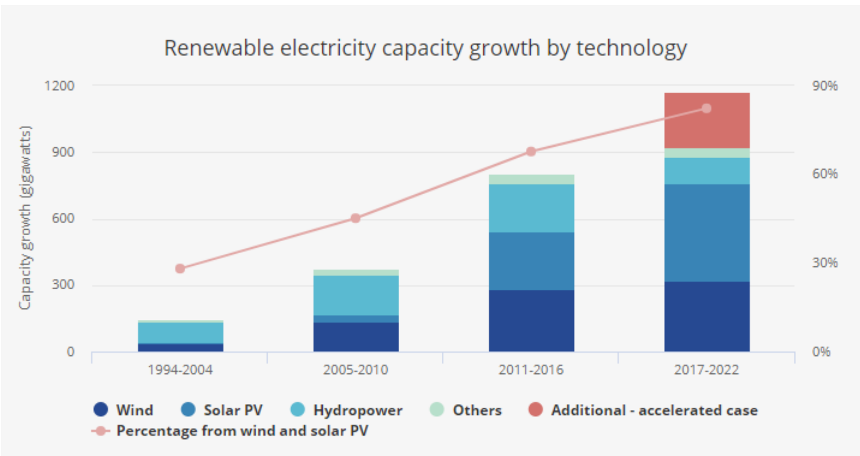

Figure 2.1: Renewable Electricity Growth 1994-2022[3]

In Figure 2.1, we can see a drastic increase of power production from renewable energy sources in the last few decades. This trend is expected to continue in near future with solar PV as the most dominant one renewable energy source.

2.2 Importance of micro-grids in modern world

Few of the most important benefits coming from microgrids are described below.

2.2.1 Economical Benefit

For transmitting power to long distances, we need high voltage transmission lines, transformers and other high voltage equipment. Such investments can be delayed if we build a microgrid near the area of demand. Moreover, the looses due to the transmission over long distances are also avoided[4].

2.2.2 Reduction in Carbon Footprints

The world is going towards resources that are environment friendly to achieve its target of CO_2 reduction. Microgrids have most of this energy production coming form RES especially from wind, solar, small hydro depending upon the region alongwith the energy storage. Moreover, recent developments of control strategies allows the integration of increasing amount of RES. So, CO_2 emissions are reduced with almost uninterruptible power supply all the time and thus also improves local energy delivery[5].

2.2.3 Security of Supply

A microgrid has the ability of operating even when not connected to the utility grid. Thus, in case of blackouts at the utility grid, the microgrid is still able to supply electricity to the consumer. Thus the stability of microgrid, even in the case of utility grid failure, is maintained which keeps voltage and frequency within allowable operating limits[6].

2.3 Microgrids' Operating Modes

Microgrid operation can be divided into two modes, described as follows.

2.3.1 Grid Connected Mode

In this mode of operation, utility grid is connected with he microgrid. When connected with he grid, microgrid usually draws power from the main grid but it can also deliver power to the utility grid if DER's are generating large power compared to the load. Bidirectional power flow is necessary for this mode.

2.3.2 Islanded Mode

In this mode, the microgrid is not connected with the utility grid and, hence, works independently to have its own generation to balance the load requirement. DERs may provide enough energy in this mode or stored energy can also be used if there is less power production from micro sources.

2.4 Micro-grids components

A typical microgrid is shown in 2.2. Due to particular technical requirements, the microgrid consists of the following major elements.

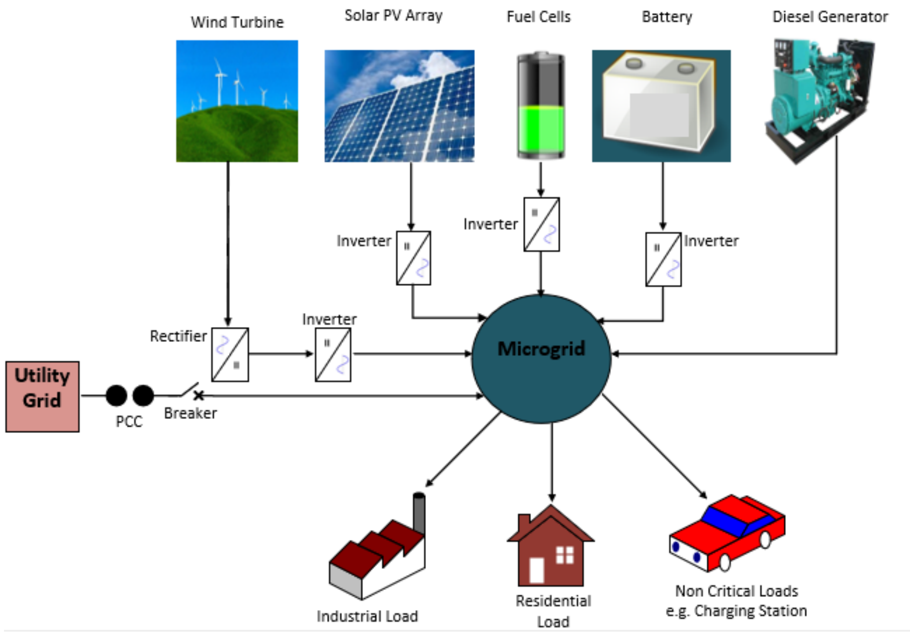

Figure 2.2: A Typical Microgrid

2.4.1 Connection Terminal

Micro-grid is designed in such a way that it has the option to connect to or disconnect from the utility grid. This interface can be achieved with a three phase electro-mechanical breaker, for example.

2.4.2 Battery Energy Storage System(BESS)

For balancing generation and demand when having only variable renewable energy sources in the microgrid, we need energy storage. Energy storage devices with proper control act immediately to balance the demand with energy supply and can even help decrease the loading of the utility network during peak load hours. Lithium Ion batteries are dominating the market for storage purposes in modern microgrid.

2.4.3 Power Electronic Converters

Power electronic converter is an important part for the integration of RES into the microgrid. Converters help us to interface RES of different electrical characteristics to a conventional AC network, allowing also the connection of the microgrid to the utility grid. Controllablity of the power flow can also be improved using converters.

Usually, power converters have two inputs.
1. Power Input
2. Control Input

Power at the input terminal of the converter is received from the different energy sources and altered according to the grid requirements through certain control schemes. A block diagram of power electronic converter is shown in Figure 2.3

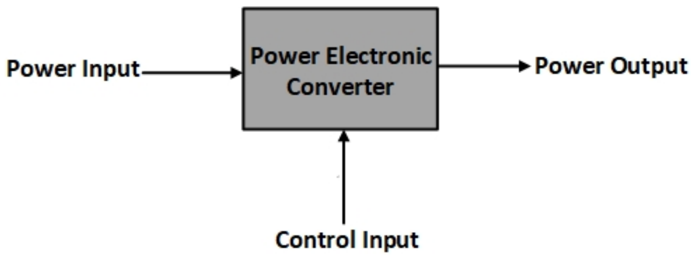

Figure 2.3: Block Diagram of Switching Converters

Disadvantages related to power electronic converters are harmonics injection to the grid and sensitiveness to system disturbances[7].

2.4.4 Central Controller

A central control system is essential for the operation of a RES dominated microgrid in a system. Normally, central controller is responsible for the following tasks in a microgrid.

- Decision whether the MG should be connected with the main grid or should work in islanded mode.
- Generates power set point for the local controllers to keep the system in balance.
- Overall communication between the modules to maintain the system stability.

2.4.5 Protection System

Protection system is the backbone of the microgrid when it comes to actions during faults. Protection system should be designed in such a way that it shifts the microgrid on islanded mode in case of a fault in the utility grid so that microgrid can provide power to its consumers without any interruption.

In case of the fault in some part of the microgrid, faulted part of the microgrid must isolate the smallest required area to remove the fault considering also the ability to balance the remaining part of the system in case of large disturbance.

2.5 Types of Loads

Loads in a microgrids can be categorized as below.

2.5.1 Critical Loads

This type of load needs good quality power without interruptions. The local energy sources and energy storage equipment must ensure the reliable and uninterrupted supply of power to these loads. Examples of these kinds of loads include hospitals and banks.

2.5.2 Non-Critical Load

The priority of such loads is lower compared to critical loads. Supply of these loads can be disconnected when there is need to stabilize the system after a disturbance. Examples may include charging station and street lightning etc.

2.6 Challenges in microgrids

Apart from benefits microgrid has also some challenges to overcome. Some of which are listed next.

2.6.1 Integration of Renewable Sources

Microgrid enables high penetration of renewables which is also sometimes a challenge for the overall system. The high amount of renewables with no rotational masses reduces the rotational inertia of the system. This reduction in inertia makes the overall system more vulnerable to disturbances and frequency deviations. One way to handle this is the implementation of synthetic inertia[8].

2.6.2 Variation of RES

Renewable energy production is stochastic in nature and can vary abruptly during different hours. It may produce more energy than needed or it may suddenly drop down to values lower than the electricity demand. Therefore, storage and coordinated control is needed if more renewable energy sources are added to a power system to avoid the power unbalance, which may result in a system failure in the worst case.

2.6.3 Transition to Isolated Mode

One of the challenges is the control of power and voltages thorough the microgrid during the transition from grid connected to isolated mode. So, control strategies need to be implemented for a safe transition.

Mismatches between load and generation may arise when transition happens from grid connected to isolated mode. Proper and fast control actions must avoid any kind of unnecessary load shedding during the transition.

3

Modelling of Micro-grid Components

3.1 Power Electronic Converters

Converter is a generic term associated with a power electronic device that converts electric power from one characteristic to another. Examples are DC-DC converters, inverters and rectifiers. Inverters are used when we need conversion of power from DC to AC and rectifiers are required when conversion is needed from AC to DC.

The output power from renewable energy sources and energy storage system is either DC or AC with non fundamental frequency so converters are needed to integrate these sources with the grid and to make this power usable for commercial and residential appliances. There are two types of three phase inverters available for this conversion process which are current source inverters (CSI) and voltage source inverters (VSI). The key difference between these two is the energy storage method on the DC side.

Semiconductor devices are the fundamental components of a converter. For power applications, inverters are preferably designed with insulated-gate bipolar transistors (IGBTs) with anti parallel diodes to make the flow of current possible in both direction. The reason for prioritizing IGBT is their high voltage ratings and lower power losses[9].

The voltage source inverter (VSI), shown in Figure 3.1, is supplied with a DC link source and output voltage in the form of a controlled three phase voltage. Voltage source converters can perform independent control of active/reactive power[10]. This ability of VSI makes it suitable for connection to weak AC networks.

The capacitor is placed at the dc link bus between the source and inverter. The main purpose of this capacitor is to stabilize the dc link voltage and reduce voltage ripple by supplying/absorbing energy during short term transients.

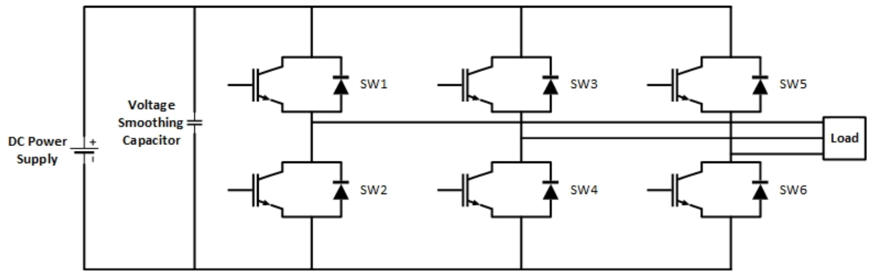

Figure 3.1: Voltage Source Inverter

3.2 Inverters' Modes of Operation

Inverters used in the microgrids have normally two modes of operation called "Grid Following Operation" and "Grid Forming Operation". In the grid following mode, the converter regulates the current injected to the grid by controlling its AC terminal voltage. This is achieved by synchronizing the inverter's voltage with the voltage of the connection point. In this mode the utility grid sets the reference for voltage and frequency of the system. In the grid forming mode, on the other hand, the inverter sets the microgrid voltage and frequency. During grid connected mode the inverter operates in the grid following mode while in islanded mode the inverters operate in the grid forming mode[11][12].

3.3 Interfacing Converter Topologies

For the successful interface of battery energy storage system and renewable energy sources with the grid, different interfacing converter topologies are used depending upon the type of energy source. These typologies are categorized according to the number of stages between the power output from the source and grid connection point.

For the energy source with DC power output such as Solar PV and battery we normally use the single stage interfacing converter but for sources such as wind turbine we need to have multi stage converters for the desired power quality[13].

3.3.1 Single-Stage Converter Topology

The input voltage at the DC side of the inverter is called DC link voltage. For any type of VSI topology, this voltage is kept constant by the inverter. As a general rule, the DC link voltage ranges from V_{peak} to 1.5 times V_{peak} of the output AC voltage of the inverter[14][15].

In single stage topology, DG source is directly connected with the converter and the output of the converter is connected with the grid. This type of topology is becoming more prominent in recent years because it has benefits of higher efficiency and less complexity due to only single stage. Figure 3.2 sketches the single stage topology.

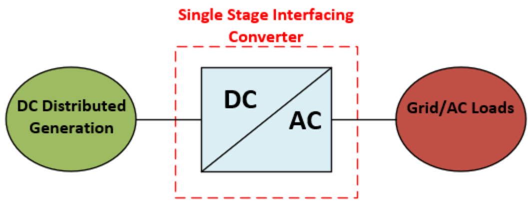

Figure 3.2: Single Stage DC-AC Interfacing Converter

The major drawback of this topology is the high ripples on the DC side which require large DC link capacitor[16]. Also, this topology requires an overrated inverter and higher dc output voltage from energy sources. In the single stage topology, multilevel inverters have been increasingly used with better DC voltage utilization and better power quality[17]. For this thesis, single stage inverter is used in order to reduce the model complexity.

3.3.2 Double-Stage Converter Topology

For PVs interfacing with the grid, two stage converter topologies are also used where the DC voltage is stepped up in the 1st stage using boost converter and then inverter converts this high DC voltage to the desired AC output voltage. This additional stage increases the losses and cost of the system. Double stage topology is shown in Figure 3.3.

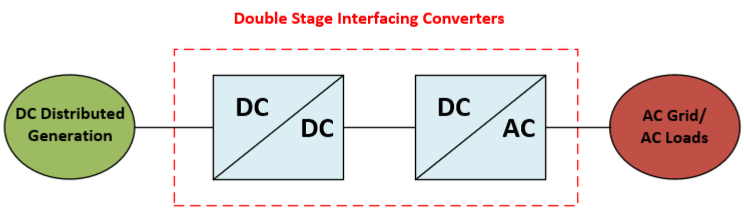

Figure 3.3: Double Stage DC-DC-AC Interfacing Converter

There are certain conditions where there can be different amount of radiations for different PV arrays due to angle difference between different panels. Due to this there might be different voltage output from different panels. Double stage topology facilitates the connection of panels exposed to different solar radiations to a common DC bus before converting to AC voltage where a common inverter can be used for inversion process.

Another case of the the double stage topology can be in wind turbine where AC power with non fundamental frequency is converted to DC and then DC is again converted to AC power with fundamental frequency as shown in Figure 3.4.

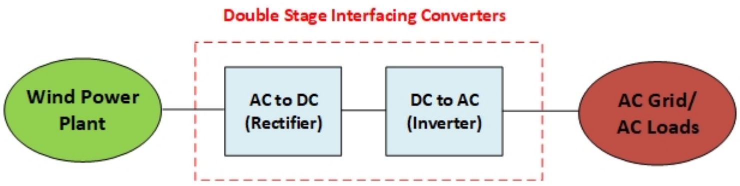

Figure 3.4: Double Stage AC-DC-AC Interfacing Converter

3.3.3 Multi-Stage Converter Topology

In the multistage converter topology, diode rectifier is used in the first stage to convert the AC output voltage to DC output voltage. Then, DC-DC converter is used to boost the DC output voltage and finally an inverter is used to convert DC voltage into AC output voltage. This topology has the advantage of high DC voltage range but it has lower efficiency and high cost compared to two stage topology[18].

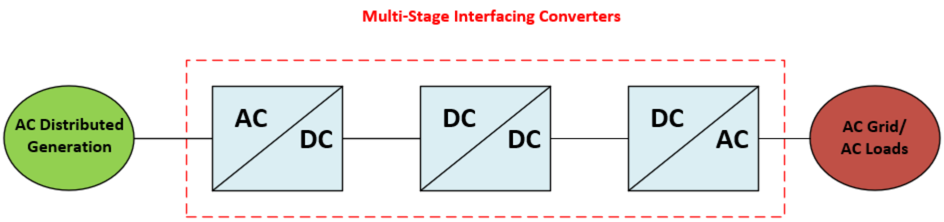

Figure 3.5: Multi Stage DC-AC Interfacing Converter

3.4 Solar PV

3.4.1 Solar PV Components

A cell is the smallest and basic unit of a solar PV. The output voltage of one single cell is too low to interconnect it to the grid. Thus, tens of these smaller units are connected together in series to form a series cell string. A group of these series strings are combined together to form a PV module. Then, these PV modules are finally connected together in series or and parallel to from a PV array to fulfill the voltage and current requirements.

All PV modules in an array are assumed identical for the sake of simplicity. The schematic of solar PV is shown in Figure 3.6. In the figure, a single solar cell, series cell string, single PV module and finally a PV array are shown, respectively from left to right.

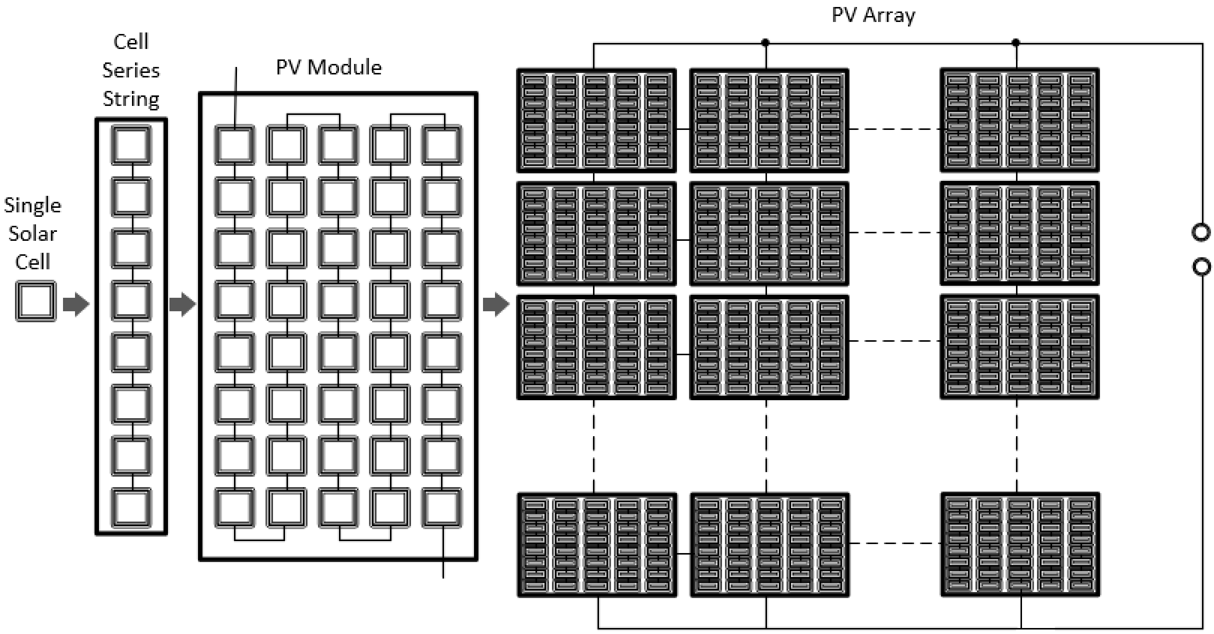

Figure 3.6: Solar PV Components

An array is connected to the inverter for converting its DC output power to AC. Normally multiple arrays are connected together in a solar PV plant.

3.4.2 Equivalent Circuit of a Solar Cell

The most commonly used equivalent electrical model of a solar PV is shown in Figure 3.7 [19]. It consists of a current source I_g, a parallel diode, a shunt resistance R_{sh} and a series resistance R_{sr}.

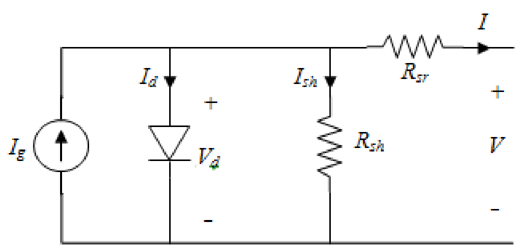

Figure 3.7: Equivalent Electrical Circuit of a Solar Cell

The value of R_{sr} affects the output voltage while R_{sh} affects the output current so ideally R_{sr} is small and R_{sh} is large. A solar cell is considered as a continuous DC current source which is dependent on the solar radiations. The amount of current is directly proportional to the intensity of radiations. The current I_g is given as

$$I_g = I_{SCR}\frac{G}{G_R}[1 + \alpha_T(T_C - T_{CR})] \tag{3.1}$$

where G is the irradiance value in W/m^2 and I_{SCR} is the short circuit current at the reference solar radiation G_R and the reference cell temperature T_{CR}. The parameter α_T is a constant and is known as the temperature coefficient of the photo current. For silicon solar cell its value is estimated as $\alpha_T = 0.0017$ A/K.

3.4.3 V-I Characteristics of Solar PV

The current and voltage output from a solar PV has an exponential curve which depends upon the irradiation. The VI characteristic curve of a solar PV is shown in Figure 3.8

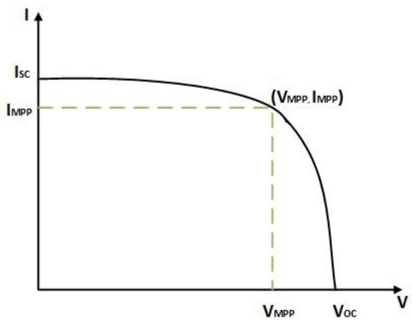

Figure 3.8: VI Characteristic of the Solar PV

The point of the maximum current output corresponds to short circuit current and the point of the maximum voltage output corresponds to the open circuit voltage. There are different combinations of V and I in the curve for different power outputs but there is only one point on the whole curve where the power output is maximum. This point corresponding to the maximum value of the power output from solar PV is referred as maximum power point(MPP). The power at the MPP is given by

$$P_{MPP} = I_{MPP}V_{MPP} \tag{3.2}$$

3.4.4 Arrangement of Modules

The output power from the PV array is the function of solar irradiance and temperature. The inverter power rating should match the maximum power output from the solar PV and its controller should regulate the voltage at the DC link according to the desired output power.

Solar PV array has been designed to produce a certain maximum power against standard irradiance and temperature values. Table 3.1 shows the configuration of the components in series/parallel to obtain the desired maximum power output and corresponding voltage, and the power output for this configuration is shown in Figure 3.9.

Table 3.1: PV Parameters for the Modelling

Number of modules connected in series per array	30
Number of module strings in parallel per array	60
Number of cells connected in series per module	36
Number of cell strings in parallel per module	1

With this arrangement shown in Table 3.1, the maximum power output of the solar PV unit is approximately 100 kW and the corresponding voltage value is around 720 V. The standard value of irradiance and temperature is 1000 W/m^2 and 25 degree Celsius respectively.

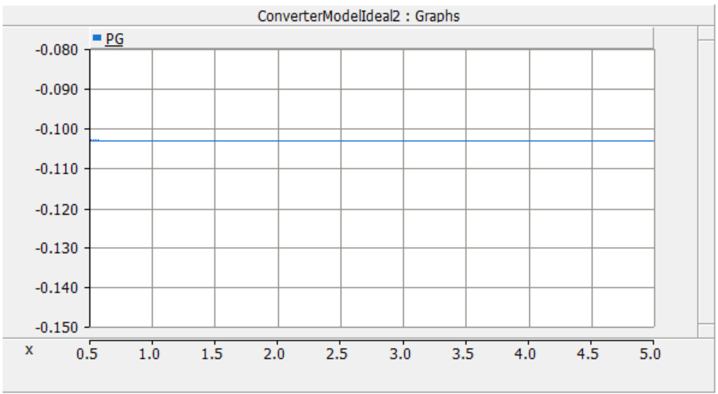

Figure 3.9: Solar output for the configuration in Table 3.1

3.4.5 Power-Voltage Characteristics of Solar PV

To obtain the power-voltage characteristic of the solar PV, simulations are performed according to the set up shown in Figure 3.10. In this setup the resistance $R1$ in series is changed and corresponding voltages and power curves are obtained.

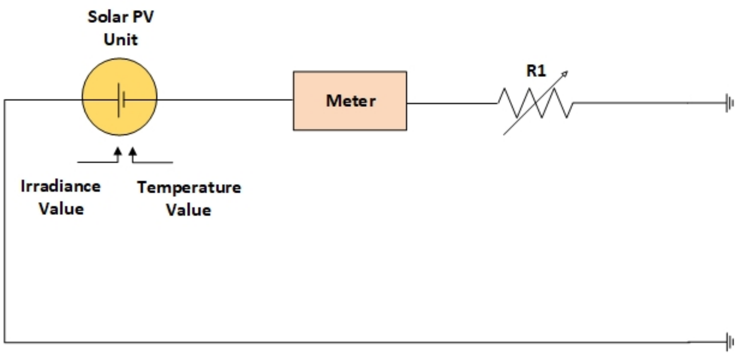

Figure 3.10: Setup for plotting the Power-Voltage curves

The test has been performed for different values of irradiance and temperature. It has been found that the value of the voltage corresponding to the maximum power point remains almost constant for the different intensity of the solar radiations as shown in Figure 3.11.

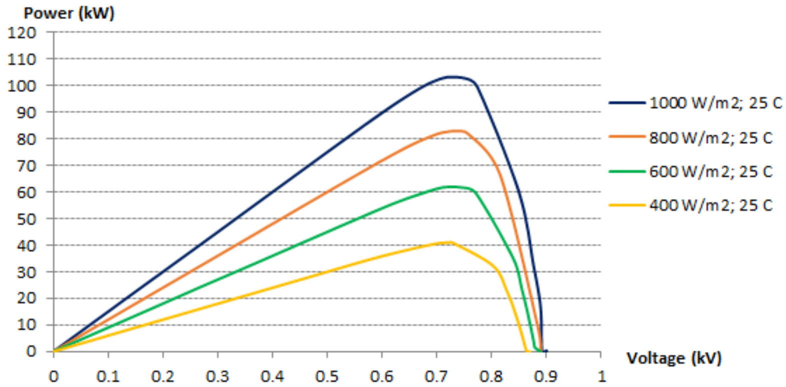

Figure 3.11: PV curves at different radiation intensities

3.5 Selection of the Battery

The battery used in the system is selected as Lithium-Ion battery due to its characteristic of high energy density and low maintenance. An equivalent electrical model of the battery is shown in Figure 3.12.

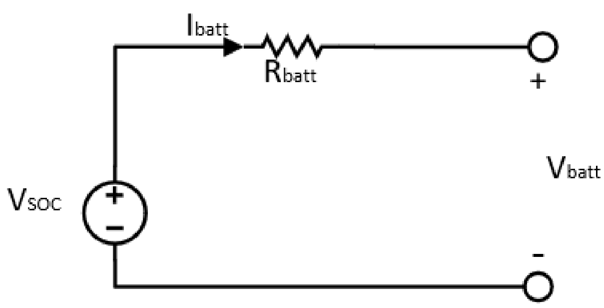

Figure 3.12: Equivalent Electrical Model of the Battery

The term R_{batt} represents the overall internal losses in the battery. Due to the internal losses in the battery, V_{SOC} is kept high e.g 1.05 p.u. so that we can get approximately 1 p.u at the terminal of the battery. The DC voltage ratings of the battery is selected as 700 V. During modelling of the battery some assumptions have been considered[20].

- Battery Resistance does not change with changing temperature so voltage drop over the entire period is assumed to be constant.
- The internal resistance of the battery is not affected by the amplitude of the current.
- The amplitude of the current does not affect the capacity of the battery.
- Self discharge of the battery is not represented.
- Charging and discharging cycles have constant value of internal resistance of the battery.
- Battery voltage and battery capacity can not be negative.

The output from the battery is connected to the inverter directly which controls the DC link voltage. The input voltage ratings of the inverter must match the voltage ratings of the battery. The equivalent model of the battery is given in Figure 3.12.

3.5.1 Sizing of the Battery

The capacity of the battery is selected so that during the emergency situation when the grid is not connected due to faulty situation and solar PV is not producing enough power, it can supply power to the load. In this thesis, following is the procedure of battery sizing.

- The maximum load has been taken into consideration while calculating the size of the battery which is approximately 70 kW.
- Back up for 2 hours is selected.
- Battery voltage of 700 volts is used to find the Ah rating of the battery.
- Battery efficiency of 0.95 is considered.

Assuming all the conditions mentioned above, the Ah rating can be calculated as:

$$AhRating = \frac{Maximum\ load}{Battery\ voltage} * \frac{Backup\ hours}{Battery\ efficiency} \tag{3.3}$$

Putting numbers into the equation 3.3

$$AhRating = \frac{70kW}{700V} * \frac{2h}{0.95} = 210Ah \tag{3.4}$$

3.5.2 Nominal Discharge Current

The batteries discharge current is often expressed as the C-rate of the battery [21]. "A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity."

Charging and discharging rates of the the battery depends upon the C rate and it decides how quickly a battery can discharge its stored energy. A 1C rate means that discharge current will discharge the whole battery within one hour. 2C rate means that battery will be discharged in half an hour. Similarly, 0.5C rate means that it will take 2 hours to completely discharge the battery.

Alongwith the ampere-rating of the battery, C-rate is also an important factor of consideration while modelling the battery. The C rating has inverse relation with the battery ampere-hour rating so if we install a high Ampere-hour rating battery we can significantly decrease the C rate of the battery. In this thesis, the value of nominal discharge current is selected as 100% which means that battery is following 1C rate to supply the power for two hours to the maximum connected load.

4

Control Techniques in the Micro-grid

In this chapter, control strategies of the microgrid will be presented. In this thesis, during grid connected mode power will be controlled at the battery converter while during isolated mode, the battery converter controls the voltage to maintain the stability of the system. It should be mentioned that, throughout this thesis, the following assumptions are made.

1. Solar PV will generate maximum power during grid connected mode.
2. Battery will not charge or discharge during isolated mode so power exchange from the battery will be zero during isolated mode.
3. Solar PV power production is always higher than the connected load.

4.1 Different Reference Frames for VSI Control

There are three different reference frames which can be described here for the control of VSI depending upon the application. These reference frames are the so called abc reference frame, $\alpha\beta$ reference frame and dq reference frame. The quantities can be converted from one reference frame to another reference frame for simplicity and better control.

4.1.1 abc Reference Frame

It is also called the natural reference frame. Both linear and non linear control strategies can be implemented in this reference frame. Examples of linear control include Proportional Integral (PI) and Proportional Resonant (PR) controllers while non linear controllers include hysteresis and deadbeat controllers. The advantage of this type of control is that we don't need to transform the parameters which makes this type of control less complicated.

4.1.2 Stationary Reference Frame

In this type of control scheme, the three phase electrical quantities are first transformed into $\alpha\beta$ reference frame, also called Clarke transformation. The result of this transformation is two-phase AC quantities. PI controller is not feasible to implement in this type of reference frame as PI controller is unable to remove steady state errors when controlling sinusoidal quantities. Examples of controllers in this type of reference frame include proportional resonant (PR) Controller. The principle of PR controller is that it has a very high gain around the resonance frequency which helps in eliminating the steady state error[22].

4.1.3 Synchronous Reference Frame

In this type of control scheme, the three phase electrical quantities are transformed into synchronous (dq) reference frame which is also called Park transformation. The advantage of this transformation is DC quantities which allow the use of integrator. For this thesis work, a synchronous reference frame has been used which allow the use of integrator to remove steady state errors.

4.2 Current Controller Design

The most common current controller block diagram for controlling the d and q current individually is shown in Figure 4.1. In this section, each term related to current controller block diagram and its performance will be discussed shortly.

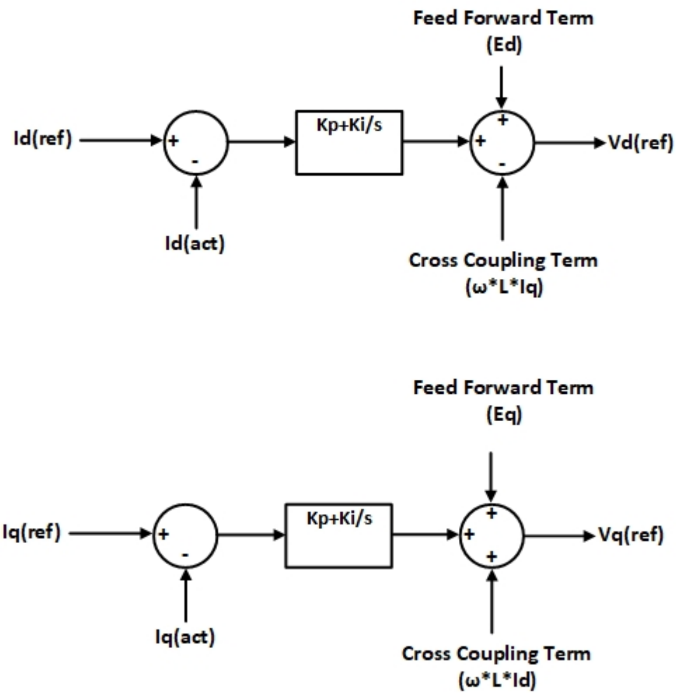

Figure 4.1: Block diagram of a current controller

4.2.1 PI Control Loop

The most commonly controller used in the modern power industry is PI controller [23] as shown in Figure 4.2. The output of the PI controller is the addition of proportional and integral term i.e.

$$CO = CO_{bias} + K_c e(t) + \frac{K_c}{\tau} \int e(t)dt \tag{4.1}$$

where

K_c = Controller gain
τ = Integral time constant
$e(t)$ = Error signal at the input of controller
CO = Controller output

The transfer function of the PI controller is given by

$$H(s) = K_p + \frac{K_i}{s} \tag{4.2}$$

where K_p and K_i are called the proportional and integral terms respectively.

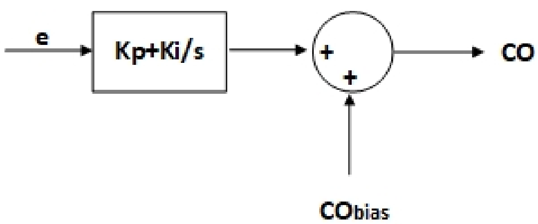

Figure 4.2: Block Diagram of a PI Controller

4.2.2 Cross Coupling and Feed-forward Terms

In Figure 4.1, it is shown that current cross coupling and feed-forward of the voltage terms are included. The cross coupling term facilitates to remove the impact of a current in certain axis (d or q) into another one while using synchronous reference frames. The feed-forward term removes the impact of variation of the grid voltage.

4.2.3 Phase Locked Loop(PLL)

For performing the transformation between different coordinates frames, Phase Locked Loop(PLL) is used to estimate the the angle of the grid voltage. The PLL block diagram is shown in Figure 4.3 which is used in this thesis to track the frequency of the grid voltage signal when the microgrid is connected with the utility grid.

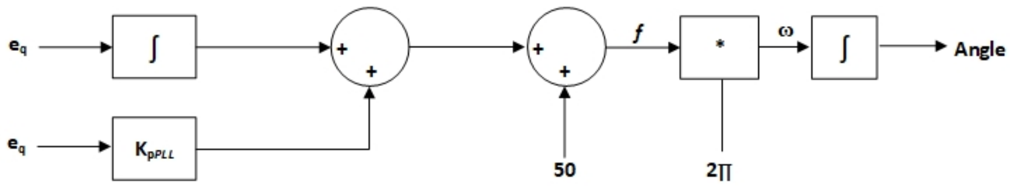

Figure 4.3: Block Diagram of PLL

For a voltage-oriented coordinate system, the PLL controller tries to force the imaginary part of the positive-sequence voltage e_{dq} to zero. Therefore, the imaginary part e_q normalized to the grid voltage is used as an angle error for the update of the grid angle and grid frequency[24].

4.3 DC Voltage Regulator

A simple DC voltage regulator is shown in Figure 4.4 which will be implemented to control the DC link voltage in the solar PV controller. In this figure Kp$_{dc}$ and Ki$_{dc}$ are the proportional and integral controller gains respectively. As solar PV unit is modelled according to its Power-Voltage curve characteristics, the power output from the solar PV will depend upon the DC voltage regulation.

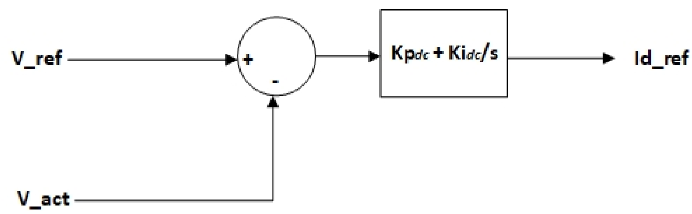

Figure 4.4: Block Diagram of DC Voltage Regulator

4.4 Grid Transition Logic

As described earlier, the microgrid must isolate itself from the utility grid in case of fault in the utility grid. Two important variables to consider in an AC system are the voltage and frequency. The frequency and voltage vary abruptly when a fault occurs. Thus, in this thesis, isolation and re-connection of the microgrid to the utility grid are decided by the RMS value of the voltage.

A voltage range of ±25% has been selected which gives the lower limit equal to 300 V and higher limit equal to 500 V. If the voltage value remains in between the 25% of the base V_{rms}, the system considers that the microgrid is still connected to the utility grid. If the value goes out of these limits, the isolation signal is activated and a command is sent to open the main breaker. The logic is shown in Figure 4.5.

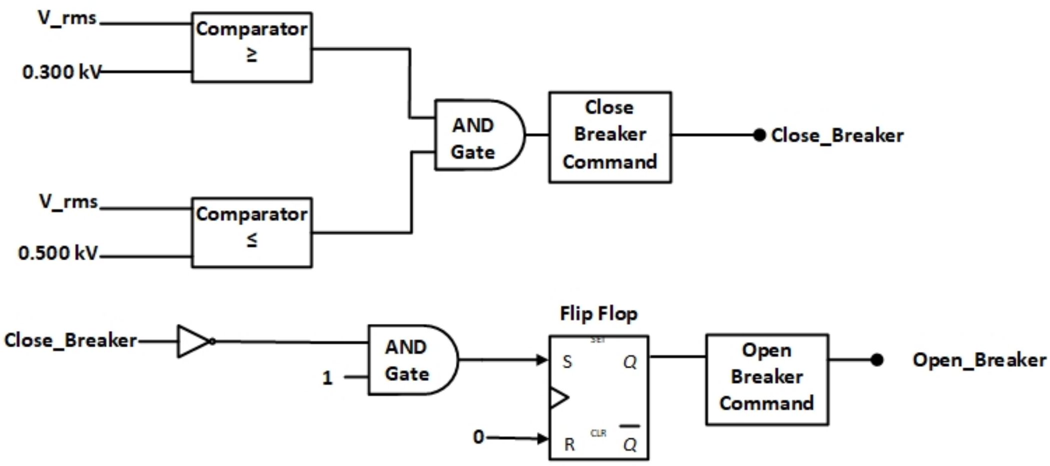

Figure 4.5: Transition Logic of Microgrid

The logic blocks are constantly monitoring the real values of the voltage of the main grid. Once the microgrid is isolated, the SR flip flop latches the signal of breaker feedback and for the rest of the simulation cycle microgrid remains isolated from the utility grid.

4.5 Controller for Solar PV

The objective of the solar PV controller is to obtain the maximum output power from the solar PV for a given value of irradiance and temperature in grid connected mode and regulate its power according to the load requirement in isolated mode. Two separate control strategies for the solar PV are implemented for the grid connected and islanded mode and are described next.

4.5.1 Control Strategy in the Grid Connected Mode

The control strategy in the grid connected mode is to produce the maximum power from solar PV unit. This is obtained by regulating the DC link voltage equal to V_{MPP} using a DC voltage regulator as shown in Figure 4.6.

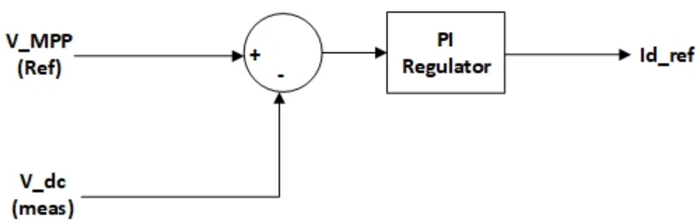

Figure 4.6: Solar PV regulator for grid connected mode

As mentioned in chapter 3, the DC voltage at the maximum power output remains constant for different values of solar radiations. For that reason, this value is used as a reference to the voltage controller when the microgrid is connected with the utility grid. In this thesis, it is assumed that the power supplied by the solar PV unit is larger than the microgrid load. Thus, the excess of power is supplied to the external grid when the microgrid is in grid connected mode.

4.5.2 Control Strategy in the Islanded Mode

In islanded mode, it might be desired to decrease the power generated by the solar PV unit in order to avoid the discharging of the battery. In this thesis, it is desired that, in islanded mode, the solar PV power is in balance with the load.

In this case, the signal ΔUdc is added to to the DC voltage regulator shown in Figure 4.7. Through the signal ΔUdc the voltage generated by the converter becomes different from the optimal, thus decreasing the power production from the solar PV unit.

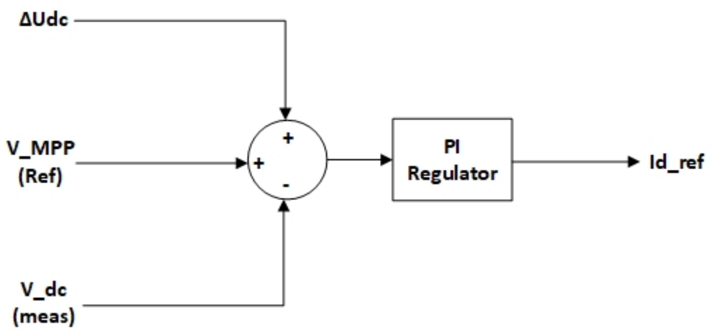

Figure 4.7: Solar PV regulator for islanded mode

The signal ΔUdc comes from secondary (central) controller, which regulates the battery power to zero when there is a transition from grid connected mode to islanded mode. The secondary (central) controller is shown in Figure 4.8.

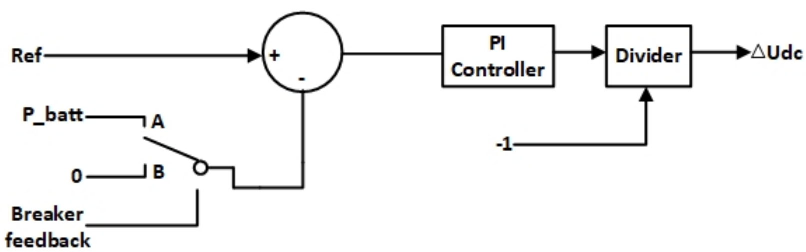

Figure 4.8: Secondary controller for islanded mode

A shown in Figure 4.8 there is a two state switch for the reference following before and after the state of transition. During grid connected mode, the switch is in position B which in practice means that the controller is deactivated. In the isolated mode, the switch goes to position A feeding then the battery power P_{batt} to the controller. Now the regulator acts to bring the battery power to zero when utility grid is not connected.

4.6 Battery Controller

For controlling the battery two different controllers have been implemented depending upon the microgrid operation mode.

4.6.1 Controller for grid connected mode

The battery inverter controller for the grid connected mode is shown in Figure 4.9 where it can be seen that basically the active power supplied or stored by the battery is controlled through controlling the d-axis current.

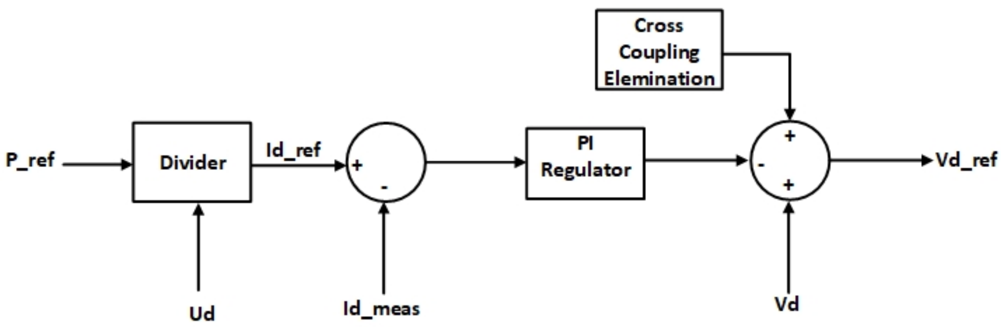

Figure 4.9: Battery controller in grid-connected mode

The value of PRef is selected according to the requirement that how much power we want to inject from battery to the utility grid. The maximum value of 1 pu means that battery will inject maximum rated power to the utility grid. Negative value of PRef is the conventional sign which shows that battery is discharging.

4.6.2 Controller for islanded mode

In the isolated mode, the battery will act as a slack source providing the voltage reference with constant frequency to the microgrid.

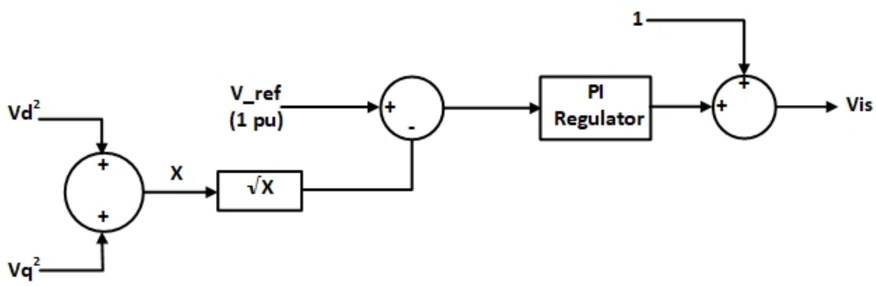

Figure 4.10: Battery voltage controller in islanded mode

In the islanded operation mode, the control strategy has been designed such that if there is a disturbance in system parameters e.g. load variation or variation in irradiance value the first one to act is battery. Then the solar PV will adjust its power output such that the power from the battery is zero.

4.6.3 Frequency Control in the Islanded Mode

As we mentioned above, when the microgrid is connected to the utility grid, the PLL is used to calculated the phase angle of the grid voltage and corresponding frequency of the system. For the islanded mode, the frequency is kept at nominal value by giving a fixed value of 50 Hz as shown in Figure 4.11

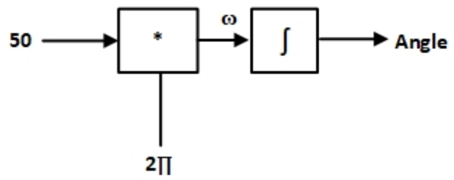

Figure 4.11: Islanded Mode Frequency Controller

4.7 Utility Grid Power Controller

For controlling the grid power in grid connected mode, a power controller has been implemented as shown in Figure 4.12. The output of this PI controller is the reference for battery regulator which was shown in Figure 4.9.

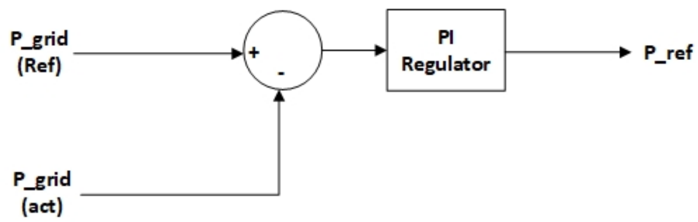

Figure 4.12: Utility Grid Power Controller

5

Types of Communication Systems in the Microgrid

Communication systems are important for the optimal and secure operation of modern microgrid because operations and control system for the renewable dominated microgrid is quite different compared to the existing conventional power systems. Thus, introducing communication systems is unavoidable for the improvement of the power system operation[25][26]. In this section, some fundamental technologies that are used in today's microgrid and types of communication architecture will be described. Architecture used for this thesis will also be highlighted.

5.1 Types of Communication in Microgrid

Due to the considerable distance between different energy sources, loads and electronic devices in a microgrid, a communication system is necessary for exchanging and sharing information between them. This data can be transmitted by using any of the following technologies.

- **Wired Technology**

  Wired technology is more reliable in transferring data compared to wireless technology. It has high data transfer bandwidth and allows point to point communication between the devices. However, the installation cost of wired technology is high. The most common examples of wired technology are Serial Communication RS-232/422/485, Bus technology (e.g. ModBus, ProfiBus,CANBus), Power-line communication (e.g. DLC, PLC, BPLC), and Ethernet/Internet of Things (IoT) (e.g. LAN, Optical Fiber Cable).

- **Wireless Technology**

  Wireless technologies have become prominent in recent years for microgrids for data transmission. They have lower data transmission ratio and are vulnerable to interference and noise but due to the cost effectiveness and easy installation they are preferred over wired technologies. Keeping in mind future expansions of microgrids, wireless technologies are better choice over wired technologies. Examples of wireless technologies include Cellular Technology(e.g.

GSM, CDMA), WiFi, WiMax, ZigBee, ZWave, Bluetooth, Insteon, Radio frequency, and Microwave[27].

A comparative analysis of all these wireless technologies has been given in Table 5.1.

Table 5.1: Comparison of various wireless technologies[28],[29]

Characteristic	**WiFi**	**Bluetooth**	**ZigBee**	**WiMAX**	**Cellular (CDMA, GSM)**
Range	50 to 100 m	10 to 100 m	10 to 100 m	Several Km	Several Km
Operating Frequency	2.4 GHz 5 GHz	2.4 GHz	868 MHz (Europe) 900–928 MHz (North America) 2.4 GHz (Worldwide)	2.3, 2.5, and 3.5 GHz	900 1800 MHz (2G) 2.1 GHz (3G)
Data Rate	54 Mbs	24 Mbps	250 Kbps	30–40 Mbps	270 Kbps
Network Topology	Point to Hub	Adhoc, small network	Ad hoc, peer-to-peer or mesh	Ad hoc, peer-to-peer or mesh	Ad hoc, peer-to-peer or mesh
Power Consumption	High	Medium	Very low	Medium	High

5.2 Types of Communication Architectures

A microgrid communication architecture can be either one of the following types.

5.2.1 Centralized Control Architecture

In a centralized architecture, there is one master control and local controllers for each source considered to be slave controllers. The central controller receives information from all slave controllers and then, depending upon the information received from local controllers, the central controller performs the necessary action and sends control signals to local controllers. Figure 5.1 shows the layout of a centralized communication control architecture. One typical example of a centralized structure is Supervisory Control and Data Acquisition (SCADA)[30].

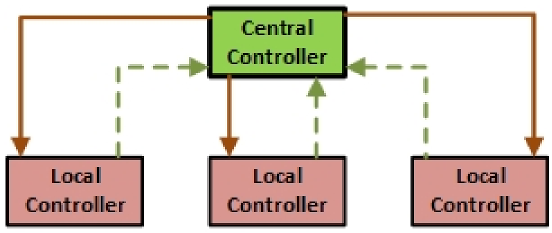

Figure 5.1: Centralized Communication Architecture

The drawback of centralized architecture is if the central controller fails, the whole system collapses. Also, size of the controller gets higher and communication network complexity increases in case of a centralized architecture.

5.2.2 Decentralized Control Architecture

As we stated in the above paragraph that centralized architecture has a very high reliance on the central controller. Due to this reason, paradigm and trends are shifting towards decentralized architectures which is also termed as Multi-agent System (MAS). As expressed in [31], "An agent is an autonomous entity that can perceive and react to its environment and communicate with others to achieve its local goal." In a decentralized communication architecture, these agents communicate and collaborate with each other for the stable system operation and hence there is no dependency on the central controller.

When it comes to the benefits of this strategy we can say that in a MAS communication architecture, all the agents within the system have identical characteristics and hence avoid master slave configuration. Another important point is if an entity fails in a decentralized architecture it does not affect the performance of overall system. The communication between agents can either be peer to peer (not involving any separate server) or non peer to peer[32]. MAS architecture is shown in Figure 5.2

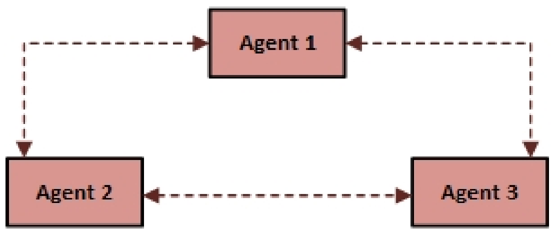

Figure 5.2: Centralized Communication Architecture

5.3 Communication Protocols in Microgrid

For two or more entities to share information among them, they have to follow a certain set of communication rules under which they can communicate with each other. This set of rules or systems which enable the entities to exchange data between them is called communication protocol. Today, there are various protocols available for communication between the devices in a microgrid and selection depends upon different factors such as communication type, data traffic, size of system and available cost etc. Nowadays, IEC 61850 has become as an international communication protocol in power industry for communication among electronic devices in microgrid or substation[33]. This protocol has the following major benefits.

1. Communication bandwidth and speed is much higher compared to other protocols.

2. IEC61850 utilizes Parallel Redundancy Protocol, under which each source sends out 2 copies of a frame, through 2 different routes. Hence, if one path fails, the data will still reach the destination via the alternative route, preventing downtime.

3. It allows information exchange and cooperation between Intelligent Electronic Devices (IEDs) from different manufacturers[34].

In this thesis, a centralized control architecture has been adopted where there is a secondary controller that acts on the battery and a solar PV regulator as a central controller and sends control signals to both local controllers of solar PV and battery units. Furthermore, the focus will be on the impact when communication failure between the devices occurs.

6

Simulation and Results

This chapter firstly describes the system under study including solar PV unit, battery unit transformer and loads. Secondly, results of base case simulations will be presented when the system is operating ideally without any communication delays. Finally, communication delays will be introduced between the controllers communication for the analysis and results will be presented.

6.1 System Description

The schematic of the microgrid used for this thesis is shown in Figure 6.1.

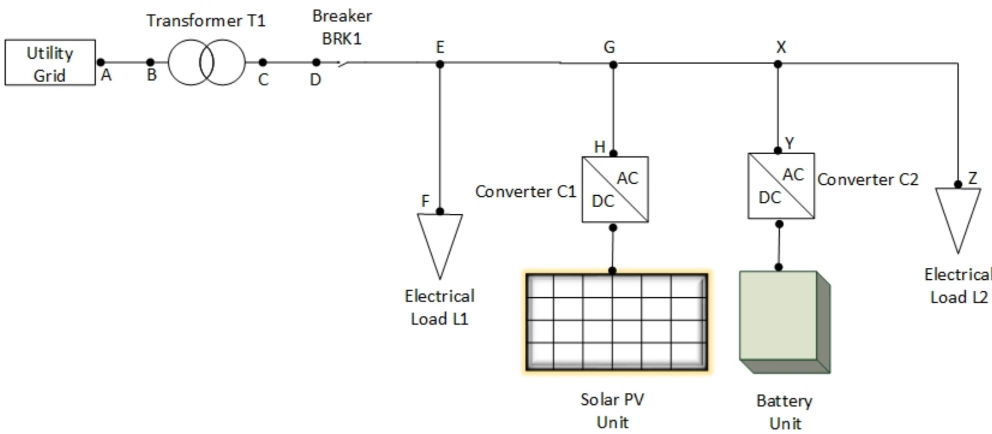

Figure 6.1: Description of the microgrid

As described earlier, microgrid model used for the thesis work has solar PV as a renewable energy source and battery for energy storage. The ratings of the components is given in the Table 6.1.

Table 6.1: Microgrid Components

Sr. No.	Description	Parameter Value
1	Battery Energy Storage System	0.7 kV; 210 Ahr
2	Battery Inverter	0.7/0.4 kV; 100 kVA
3	Solar PV Maximum Power	≈ 100 kW
4	Solar PV Inverter	0.7/0.4 kV; 125 kVA
5	Maximum Load	≈ 70 kW

Three phase ΔY distribution transformer is connected between the point of PCC and 20 kV transmission line. The specifications of the transformer is given in the Table 6.2

Table 6.2: Transformer Specifications

Sr. No.	Parameter Description	Parameter Value
1	Power rating of the transformer	125 kVA
2	Winding connection	Δy
3	Positive sequence leakage reactance	4 %
4	Primary voltage	20 kV
5	Secondary voltage	0.4 kV

In Table 6.3, cables specification are described which have been used in the thesis work. The values have been taken from[35]. All cables are mentioned according to the nodes as shown in Figure 6.1.

Table 6.3: Cables Specifications

Sr. No.	Node	Distance b/w nodes (m)	Line Type	R_ph (ohm/km)	X_ph (ohm/km)
1	A-B	10	4x120 mm^2Al	0.284	0.083
2	C-D	5	4x120mm^2Al	0.284	0.083
3	E-F	30	4x6 mm^2Cu	3.690	0.094
4	G-H	30	4x35 mm^2Cu	0.574	0.294
5	X-Y	30	4x16 mm^2Cu	1.380	0.082
6	X-Z	30	4x25 mm^2Cu	0.871	0.081

The values of the reactor inductance, reactor resistance and DC link capacitor, shown in Figure 6.2, for battery inverter and solar PV inverter are given in the Table 6.4.

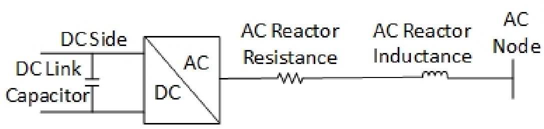

Figure 6.2: Converter schematic with electrical components

Table 6.4: L,R and C Values

Sr. No.	Element	Battery Inverter	Solar PV Inverter
1	DC link capacitor	5102.04 μF	4897.959 μF
2	AC reactor inductance	0.407437 mH	0.424413 mH
3	AC reactor resistance	1.28 mΩ	1.33 mΩ

6.2 Base Case Simulations

This section describes the base case simulation i.e. without any kind of communication delays during the transition and for both solar and battery controller.

6.3 Battery power regulation with excess power from Solar PV

In this section, the simulation results are obtained when the microgrid is operating in **islanded mode**. Also, as mentioned previously, in this thesis the maximum power of the solar PV is always assumed to be greater than the load. The control strategies for the islanded mode have been described in Chapter 4.

6.3.1 Constant load with variation in solar radiation and power production

The system is operating in islanded mode in steady state. There is no variation in the load but irradiance value is varying momentarily because of cloud effects, for example. The simulation sequence is as follows

@**t=0 s**: Simulation starts with irradiance = 1000 W/m^2 and Load = 68 kW
@**t=1.5 s**: Irradiance value goes down to 750 W/m^2
@**t=3 s**: Irradiance value increases upto 900 W/m^2
@**t=4 s**: Irradiance value goes down again to 800 W/m^2

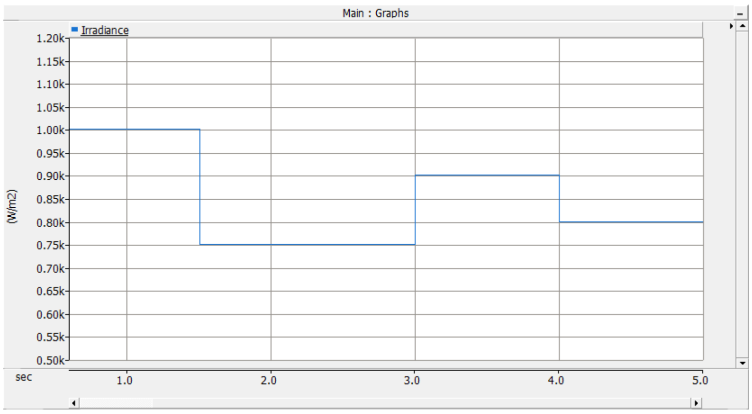

Figure 6.3: Battery controller in grid-connected mode

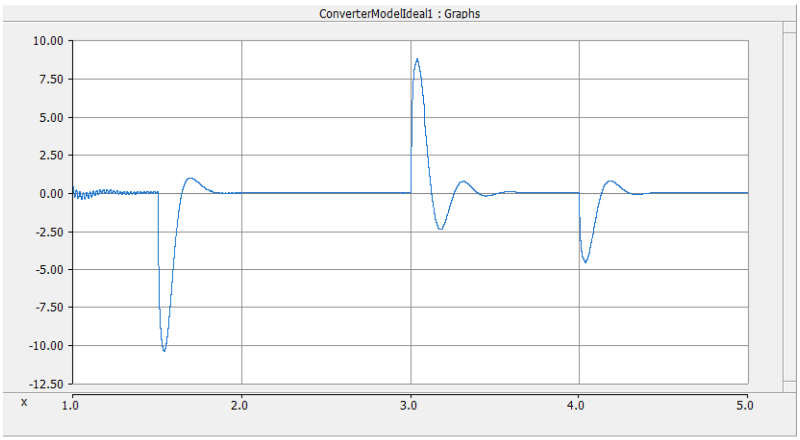

Figure 6.4: Battery Inverter Power Output

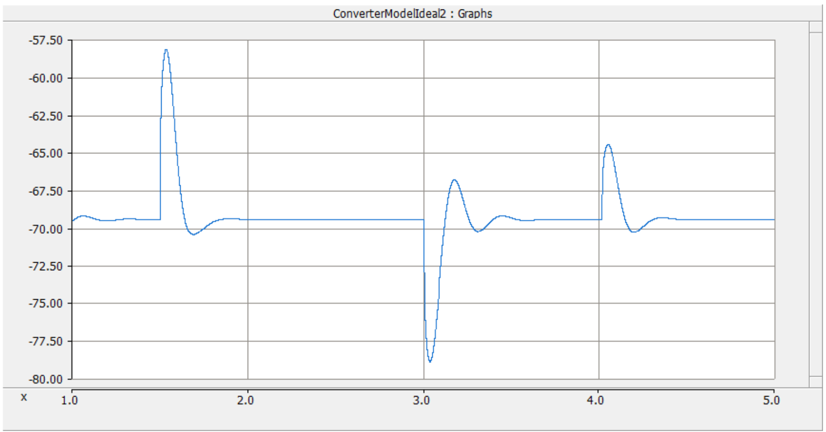

Figure 6.5: Solar PV Output

Figure 6.3 shows the variation in irradiance value while Figure 6.4 and Figure 6.5 show the results of power output from battery and solar PV inverters respectively. From the figures it can be seen that the final battery power exchange is zero according to our control strategy in islanded mode. Solar PV unit adjusts its out put power according to the load requirement as per its control strategy in islanded mode.

6.3.2 Constant irradiance with variation in load

The microgrid is again operating in islanded mode.This case investigates the system performance when there is variation in the connected load but the irradiance value on the solar PV unit is maintained constant to a value of 800 W/m^2. The simulation sequence for this case is as follows:

@ **t=0 s**: Simulation starts with Irradiance = 800 W/m^2 and load = 55.5 kW
@ **t=2 s**: Load of 42.75 kW is disconnected and the maximum connected load is 12.75 kW
@ **t=3 s**: Load increases and total connected load is 25.35 kW

@ **t=4 s**: Load of 12.75 kW is disconnected and total connected load is 12.6 kW

As per the control strategy of the solar PV , the controller immediately responds to keep the power flow in balance while there is variation in load. The voltage on the DC link of the PV unit is regulated and brings the solar power to match the load according to the Power-Voltage curve of the solar PV. Figure 6.6 and Figure 6.7 show power output from battery and solar PV respectively.

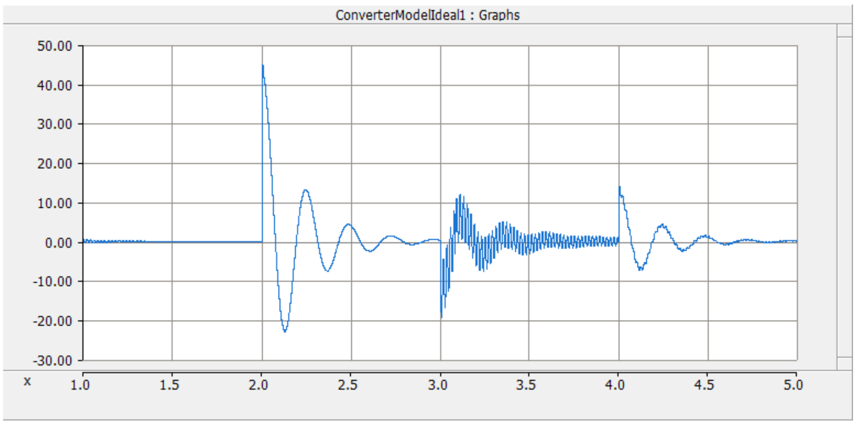

Figure 6.6: Battery Inverter Power Output

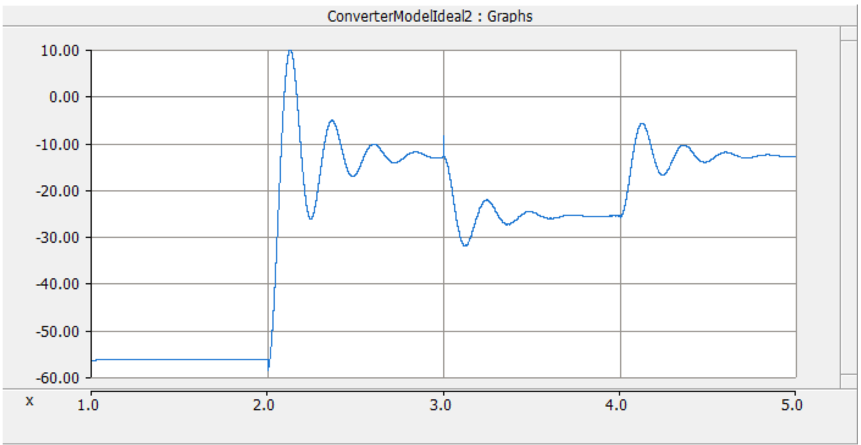

Figure 6.7: Solar PV Output

Battery power in this case remains at zero value because the solar PV is able to meet the load.

It can be noted that compared to the previous case, more oscillations are observed in this case. This might be because we face large difference between the load and generation and the controller needs to respond more aggressively to have balance between them in case of variations compared to the previous case.

6.4 Transition from Grid-connected to Islanded Mode

6.4.1 Large Generation of Solar with Constant Load

In this case, the load is kept constant and the solar PV unit produces more power than the load. The battery unit is also capable of providing power as it is charged. The remaining extra power from solar PV along with the battery power will flow to the utility grid as long as microgrid is connected with the utility grid.

A three phase fault occurs at t=2 s thus the RMS voltage decreases below the minimum limit, the main breaker opens and the microgrid isolates itself from the utility grid. The breaker opening event is communicated to the battery unit controller, which makes it to switch from the grid connected mode to isolated mode immediately, assuming that there is no delays in the communication channel.

In isolated mode, the battery unit controller regulates its power to zero value as there is excess power from solar PV. The voltage value on the DC link of the PV inverter is adjusted such that the power production from solar PV is reduced after transition according to the load requirement. The PV power generation is balanced with the connected load after the controllers act and system reaches new steady state values.

Table 6.5: Steady-state power values before and after the transition

G (W/m2)	P_L (kW)	PV Power (kW)		Battery Power (kW)		Power to grid (kW)	
		Before fault	After fault	Before fault	After fault	Before fault	After fault
1000	68	103.1	69.4	124.9	0	152.53	0
800	68	82.58	69.4	125	0	133.79	0

Two different radiation values have been selected for the case analysis as shown in Table 6.5 and the battery produces 125 kW . The excess amount of power from solar PV and the power from battery flows towards the utility grid before the fault, but, after the fault, the battery power is regulated to zero and solar PV adjusts its power according to the load requirement. After transition, no power flows towards the utility grid as the microgrid is disconnected from the utility grid.

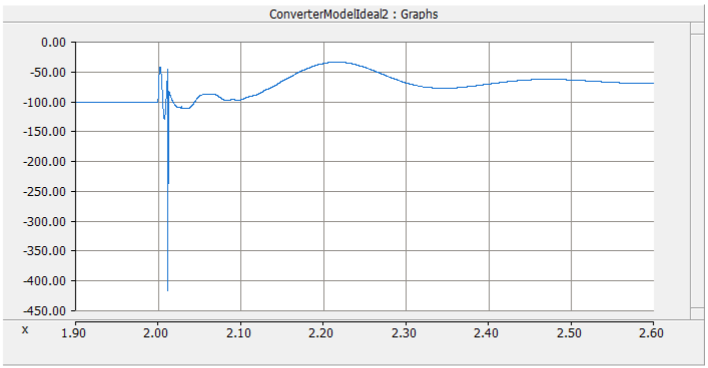

Figure 6.8: Solar power @ Irradiance = 1000W/m^2

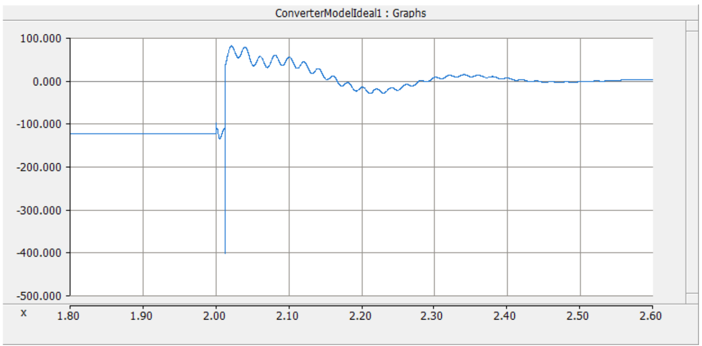

Figure 6.9: Battery power

Figure 6.8 and Figure 6.9 show the solar and battery powers respectively for this particular case. The case has also been summarized in Table 6.5.

6.5 Simulations considering communication delays

In this part, communication delays will be introduced between controllers in order to investigate their impact on the system performance.

6.5.1 Transition from Grid Connected Mode to Isolated Mode

The control of the power output from both microgrid sources i.e solar PV and battery depends upon the mode of operation of the microgrid. The battery controller has two different control strategies for both modes so it is important for the control scheme to have the feedback of the operating mode so that it can switch its control strategy. Different time varying delays between the communications of the controllers may have significant impact on the performance of the inverters. The information of the status of the main breaker (BRK1) is assumed to be transmitted through communications. As discussed in Chapter 4, the battery controller switches from power control mode to voltage control mode when an opening of breaker BRK1 is detected. The delay is introduced as shown in Figure 6.10.

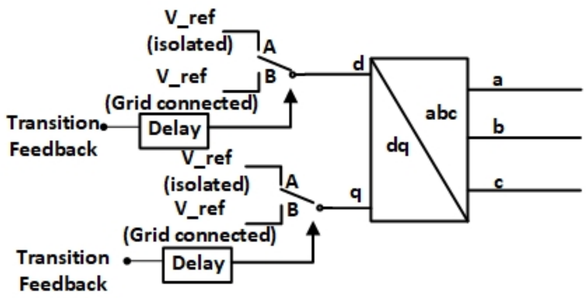

Figure 6.10: Delays in the transfer of voltage references

The controller follows the reference according to the grid connected mode as there is delay in the feedback of breaker which disturbs the voltage and power values during the delayed time. Although delay is introduced only in the controller of battery, it also effects the output power of solar PV unit due to the fact that the signal of battery power regulator output i.e. ΔUdc is also an input to solar PV controller to adjust the solar PV inverter's output power during the isolated mode. In Figure 6.11 and Figure 6.12, a comparative analysis of the active power from battery and solar PV is shown for different time delays which occur in the feedback of transition. The curves in the following figures show a comparison when system returns to a steady state after some transients.

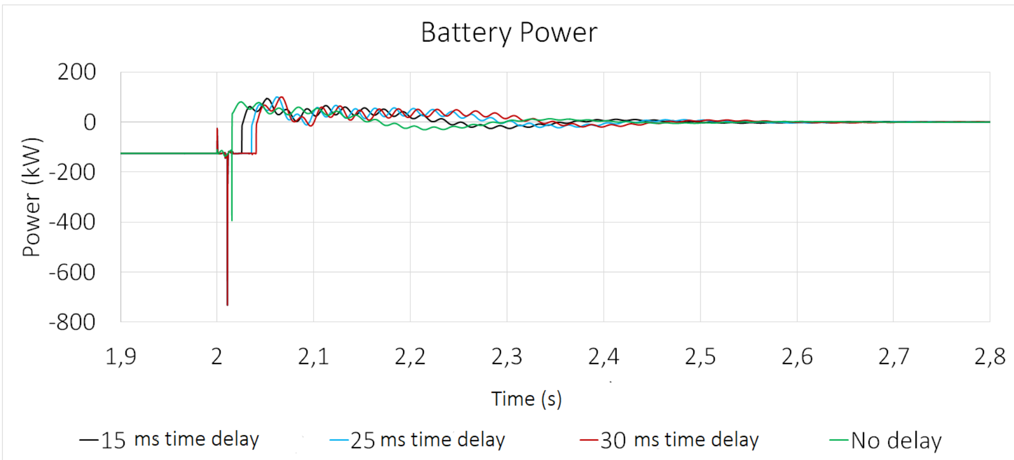

Figure 6.11: Battery power comparison with different time delays

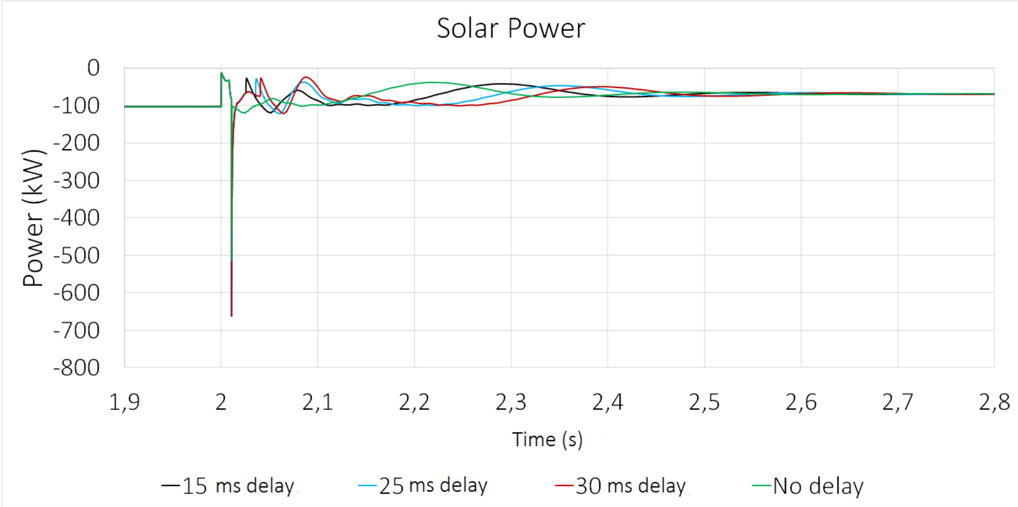

Figure 6.12: Solar power comparison with different time delays

6.5.1.1 Analysis

For a communication delay of 35 msec or above between the transition feedback, the system turns unstable and this has been analyzed for different values of radiations and with different amount of load connected to understand if these two factors have any impact on the stability when the delay occurs. It is observed that these factors do not have an impact on the time delay that causes instability. This statement has been verified for the values of loads and solar radiations given in Table 6.6.

Table 6.6: Radiation and load values for the cases

Sr. No.	Load Value (kW)	Radiation Value (W/m^2)
Case 1	68	800
Case 2	68	1000
Case 3	26	800
Case 4	26	1000

6.5.2 Delays in the Battery Secondary Power Controller

The battery power regulator is shown in Figure 4.8 which is responsible for regulating the battery power to zero when microgrid is isolated form the utility grid. In this section, we will observe impact on the system in case of delay of the communication channel which is giving input of the battery actual power to the controller as shown in Figure 6.13. The delay impact will be studied after microgrid switches form grid connected mode to isolated mode.

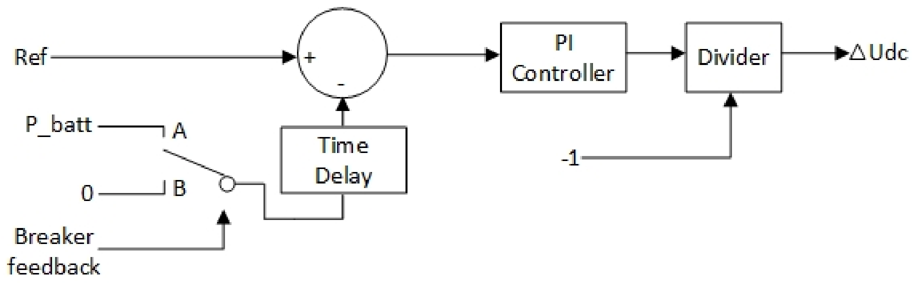

Figure 6.13: Delay in battery power input signal

As shown in Figure 6.13, the battery power regulator experiences a delay in regulating the actual power of the battery after the transition mode which disturbs the operation of both parallel inverters and it takes longer time to regulate the power output from the inverters with increased delays in the feedback of battery power. Eventually, system goes to the state of instability @ time delay of 55 ms. The power output from battery inverter and solar PV inverter is shown in Figure 6.14 and 6.15 respectively.

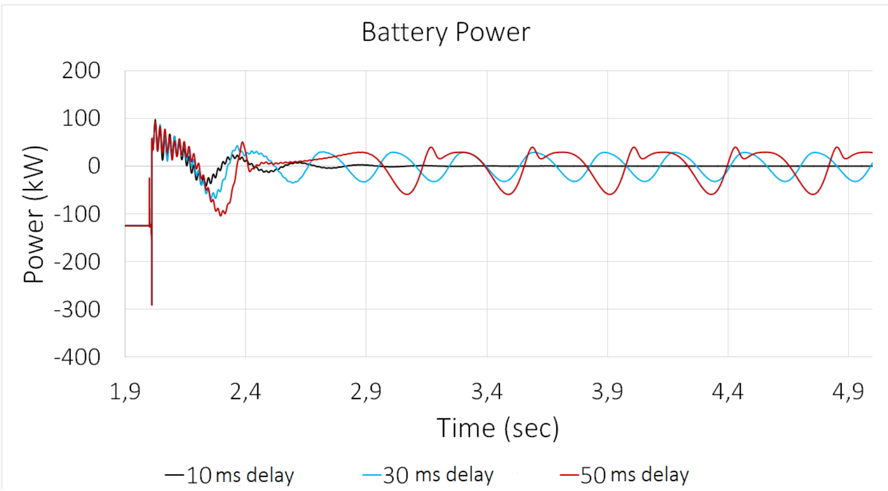

Figure 6.14: Battery power output for different time delays

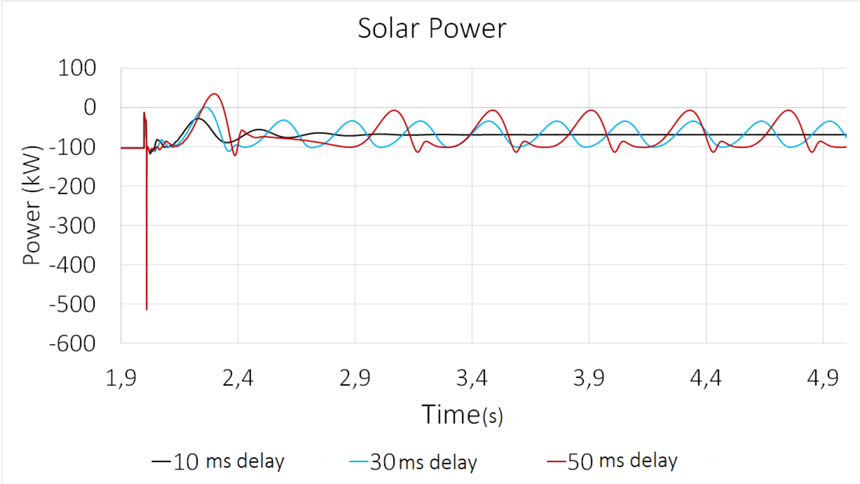

Figure 6.15: Solar power output for different time delays

This case has also been studied for different combination of parameters i.e. load and irradiance. After analyzing different combinations, it has been found that irrespective of the load or irradiance values when solar PV is generating power closer to the connected load, the system remains stable even at the longer time delays than 55 ms. One reason for this can be that secondary controller does not have to compensate for a larger difference after the fault occurs since the battery controller acts immediately so it is easier to remove smaller difference in shorter time which is helpful in keeping system alive. The case investigated for different loads and solar irradiance values is shown in Table 6.7.

Table 6.7: Analysis of the case under different conditions

Sr.No.	**Irradiance Value** (W/m^2)	P_L (kW)	**Time Delay** (55 ms)	**System Status**
1	1000	68	55	Unstable
2	800	68	55	Stable
3	1000	90	55	Stable
4	1200	90	55	Unstable
5	300	26	55	Stable

6.5.3 Delays in the Solar PV Regulation

As shown in the controller of solar PV i.e. Figure 4.6 , it produces maximum power in case of grid connected mode and adjusts its power according to the load connected in the isolated mode. For adjusting its power to match the value of the connected load the output signal of the battery power regulator comes to the solar PV voltage controller so that it can reduce its power accordingly in islanded mode. In this case, the delay is introduced in receiving this signal in the islanded mode as shown in Figure 6.16.

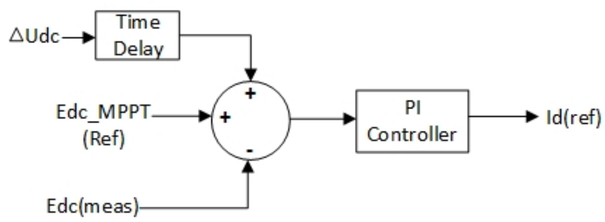

Figure 6.16: Delay introduced int he solar PV power regulator

The delayed signal disturbs the d current value of the voltage regulator and power outputs from solar PV inverter and battery inverter take longer time to reach the steady state values. Figure 6.17 and Figure 6.18 show the power outputs from battery and solar inverters respectively.

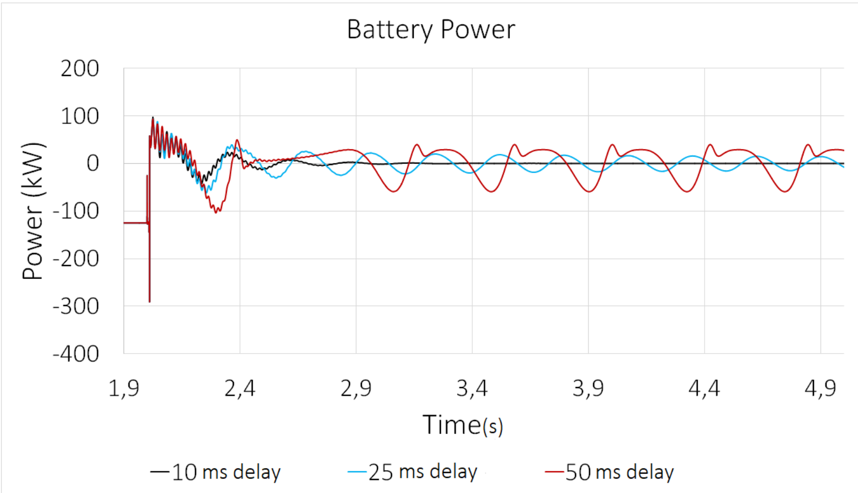

Figure 6.17: Battery power output for different delays

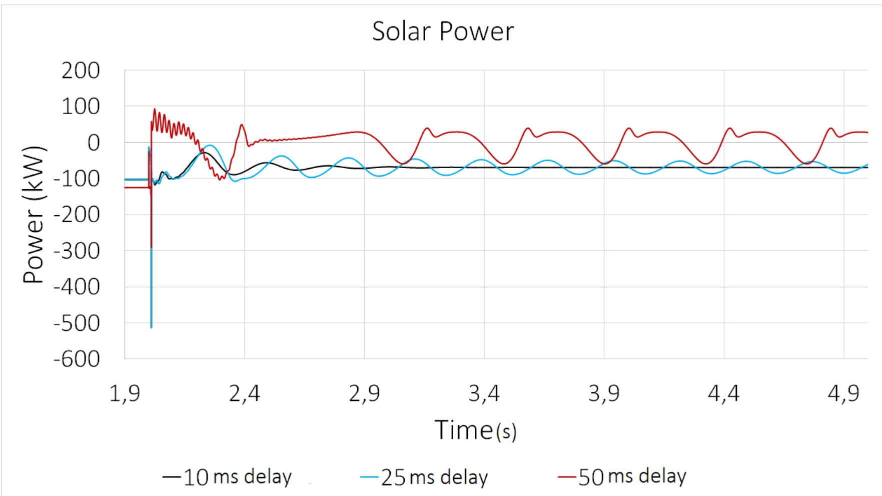

Figure 6.18: Solar power output for different delays

The case has been analyzed for different combination of parameters i.e. load, irradiance. After analyzing different combinations, it has been found that irrespective of the amount of load or irradiance when solar PV is generating power closer to the connected load the system avoids instability even after 50 ms. One reason for this can be that controller does not have to compensate for a larger difference after fault occurs so it is easier to remove smaller difference in shorter time which is helpful in keeping system alive. The studied cases are summarized in Table 6.8

Table 6.8: Analysis of the case under different conditions

Sr. No.	**Irradiance Value** (W/m^2)	P_L (kW)	**Time Delay** (55 ms)	**System Status**
1	1000	68	55	Unstable
2	800	68	55	Stable
3	1000	90	55	Stable
4	1200	90	55	Unstable
5	300	26	55	Stable

6.6 Delays in communication in islanded mode

In this section, base case simulation results will be analyzed when there is delay in coordination between the converters' controllers while microgrid is operating in islanded mode.

6.6.1 Constant Load with Variation in Irradiance

This section describes the system behaviour when system is operating under constant load but irradiance value is varying as in section 6.3.1 but for this section we will have communication delays between the controllers which is shown in Figure 6.19.

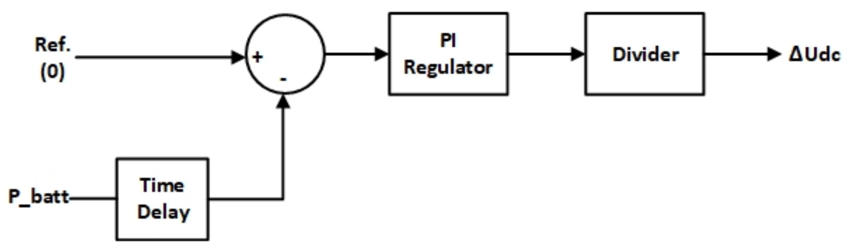

Figure 6.19: Battery power output for different delays

The simulation sequence is as follows

@**t=0 s**: Simulation starts with irradiance = 1000 W/m^2 and Load = 68 kW
@**t=1.5 s**: Irradiance value goes down to 750 W/m^2
@**t=3 s**: Irradiance value increases upto 900 W/m^2

The power output from the battery unit inverters solar PV inverter is shown in Figure 6.20 and Figure 6.21 respectively. As we can see here, compared to Section 6.3.1, there are more variations in the power output from the inverters and the oscillation keep on increasing as the communication delays increase. We can also observe here that delays between the information transfer increases between the controllers it becomes difficult for the controllers to go to steady state values and they keep on integrating the error values and eventually system goes to the state of instability when the delay increases beyond 60 ms.

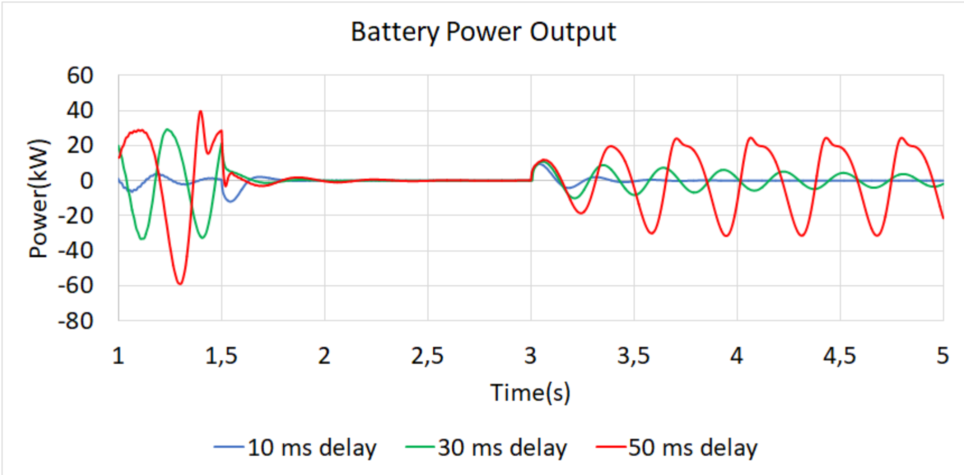

Figure 6.20: Battery power output for different delays

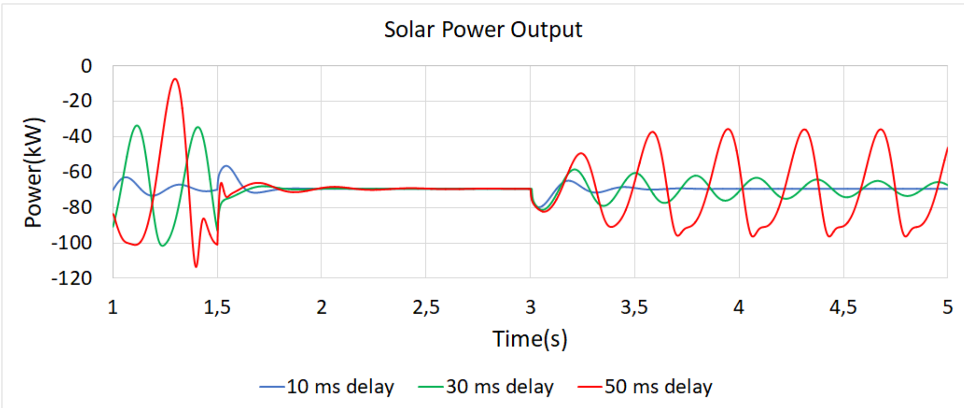

Figure 6.21: Solar power output for different delays

6.6.2 Constant Irradiance with Variation in Load

This section investigates the system performance when system operates under constant irradiance value but connected load is varying as in section 6.3.2 but for this section we will have communication delays between the controllers as shown in Figure 6.22.

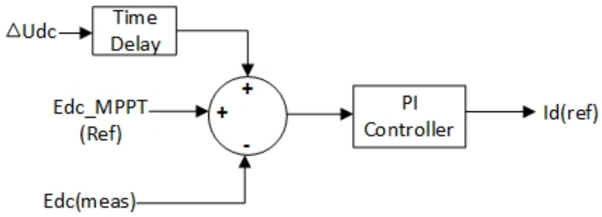

Figure 6.22: Delay introduced int he solar PV power regulator

The simulation sequence is as follows
@ **t=0** s: Simulation starts with Irradiance = 800 W/m^2 and load = 55.5 kW
@ **t=2** s: Load of 42.75 kW is disconnected and the maximum connected load is 12.75 kW
@ **t=3** s: Load increases and total connected load is 25.35 kW
@ **t=4** s: Load of 12.75 kW is disconnected and total connected load is 12.6 kW

The power output from the battery unit inverters solar PV inverter is shown in Figure 6.23 and Figure 6.24 respectively. As we can see from the figures, that oscillation are very much prominent in this section compared to section 6.3.2 and also compared to section 6.6.2. the controllers are unable to regulate their power as per ideal situation because of the system transients.

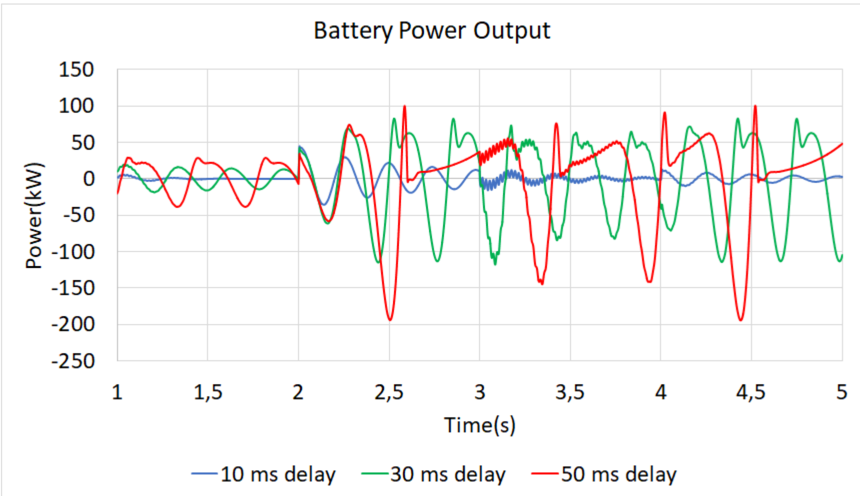

Figure 6.23: Battery power output for different delays

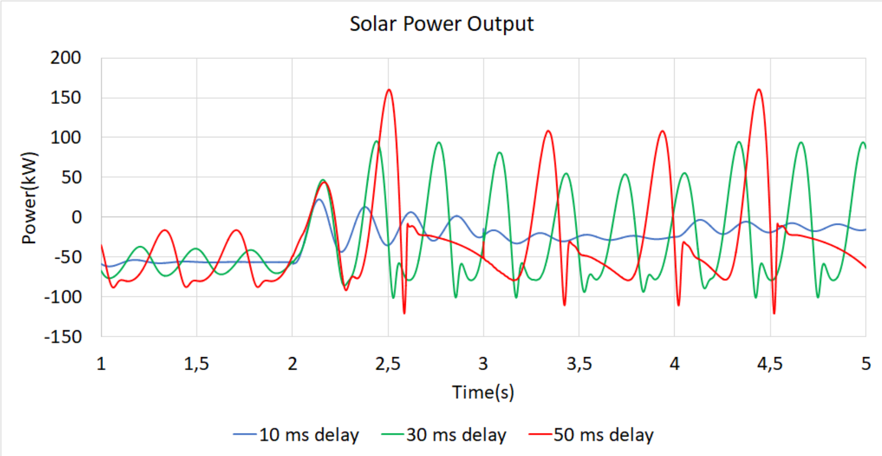

Figure 6.24: Solar power output for different delays

7
Conclusion and Future Work

7.1 Conclusion

The impact of different communication delays in a microgrid system composed of solar PV and battery units as its own energy sources has been studied in this thesis. The microgrid is connected with utility grid trough a transformer and breaker but also capable of disconnected form it. Thus, the system under study is implemented with two different control strategies for grid connected and islanded mode. For such operation modes, controllers have been implemented accordingly.

In grid connected mode, a power controller has been implemented such that the power exchange between the microgrid and the utility grid remains constant. In this case, the battery output power is regulated to obtain the desired power exchange. In islanded mode, a secondary controller has been implemented such that the power from the battery unit is zero. This is achieved by regulating the power output from the solar PV unit to match the load consumption.

The system performance has been studied considering the following different cases.

1. Transition from grid connected mode to islanded mode.
2. Microgrid operating in islanded mode.

It has been found that the system is proner to instability when there is delay in information exchange during transition from the grid connected mode to the islanded mode. Delays in the signal that indicates the status of the breaker that connects the microgrid with the utility are the most adverse ones compared to the delays in other parts of the system, such as the battery controller or the solar PV controller. This might lead to the complete collapse if delays exceed a certain time, which, in the particular system studied in this thesis is around 35 ms.

In islanded mode, the solar PV controller is tested by varying the solar irradiance and load. It is found that, in the case of solar irradiance variation, the system can turn unstable for communication delays greater than 60 ms. On the other hand, in the case of load variations, it is observed that the transients are more severe compared to the previous case.

It should be mentioned that the time delays can go greater if the amount of power injection capability by the solar PV is very close to the load demand. This is due to the fact that, in these cases, the controllers have to compensate for a smaller mismatch compared to when the differences are significant.

7.2 Future Work

There are some important points which can be studied for future work.

1. For this thesis work, single stage topology of the converters is used by having an assumption that all solar PV arrays are alike and generating the same amount of output voltage. For future work, one can look into more practical case when voltages of the solar PV arrays vary and double stage topology is needed for having same amount of voltage at the input of inverter before inversion.

2. This thesis work included only solar PV unit and battery energy storage system. For future work, wind turbine can be integrated into this model if expansion of the system is needed in the future. This will follow the same procedure i.e modelling of the wind turbine and then implement some control strategies to control the output power from wind.

3. In some literature, it is said for a good performance of the DC voltage control another type of controller called Fuzzy Controller can be used which has two inputs. One input is the error between reference and actual signal and the second input is the representation of the variation of this error[36]. So I would suggest to use Fuzzy Controller in case where irradiance value is changing frequently.

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