Emergency-Power Substation PCM System-PV Backup System

by

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ABSTRACT

Protection, control, and monitoring (PCM) systems are vital components in electric power substations. Devices used in PCM systems require a DC power source to function properly. The operation and automatic control circuits, protective relay system and emergency circuits are powered by substation batteries. In case the batteries lose the primary power source (the grid), the substation will not react to unplanned events that could occur on the system which could cause significant losses without the proposed photovoltaic (PV) Backup system. Further, it could be severe, depending on the type of loads are fed from the substation.

In case of a blackout or an unplanned power outage the existing battery backup system will not be able to last for more than few hours, which creates the need for a more reliable and renewable power source that would keep a PCM system of a substation working efficiently.

This thesis proposes a design of a photovoltaic system that powers protection, control, and monitoring devices in an electric power substation as an emergency backup system for the primary power source, the Power Grid, which feeds the DC auxiliary system.

The main drive for the proposed system is to increase the reliability of the primary power source that feeds critical loads in a power substation and to have it as an available emergency backup source.

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To my mentor and former director Mark Zwolinski thank you for all your support and guidance which allowed me to be where I am today. To my parents and siblings for your continued love and support that you have always given me.

Chapter 1: Introduction

1.1 Introduction

It is vital for electrical utility companies to prevent problems in the electrical supply system as well as adopting modern maintenance practices to keep the continuous improvement of performance and power supply quality indexes. A major differentiating factor in the power quality is the prevention of faults and defects in the power systems [1]. To achieve this objective, a protection, control, and monitoring (PCM) system must exist in a power substation.

Protection, control, and monitoring (PCM) system in an electrical substation requires an independent DC power source which does not vary with the main source that being monitored. Batteries are used to provide DC power for PCM system in a power substation.

PCM system in a substation depends entirely on batteries and they can only last for few hours if there is an unplanned power outage, which creates the need for a reliable backup source.

In an unpredictable disaster situation, the power could be out for days. The existing battery powered backup system could only support hours of operations. This thesis proposes a design of a Photovoltaic (PV) system to work as a backup source to feed the battery charger/batteries that feed Protection, control, and monitoring (PCM) system of a power substation for a longer period.

1.2 Objectives

The main objectives of this Thesis are:

- Propose a system that increases the reliability of critical protection control and monitoring equipment in a power substation by having a photovoltaic (PV) system used as a backup for utility to feed PCM system in a power substation.
- To simulate the proposed design using MATLAB/SIMULINK.

Protection, control, and monitoring system of a substation is the foundation for automating the grid. It allows you to see what happens in the grid and ensures a reliable uninterrupted operation anywhere and anytime. To ensure the reliability to the PCM system of a substation a more reliable backup power source is needed. In this thesis a photovoltaic system has been designed to be used as a backup power source to feed protection, control, and monitoring system in a substation using MATLAB/Simulink for simulation.

1.3 Literature review

The study of this thesis depended on some previous studies that are mentioned in this section.

PV Powered DC System for Protection Control and Monitoring (PCM) in Substations. This paper proposed a hybrid PV solar system to feed the protection, control and monitoring system in a power substation. The proposed system was designed to feed 220/33kv sub-station located at "Masjid Moth Delhi, India". A PV capacity of 9 kW, 110 battery, 3 kW convertor capacity have been used. The proposed system in this paper consists of PV array, charge controller, DC/DC converter, charging source selector and battery bank. The DC source selection switch is what controls the source to feed the critical DC loads based on source availability. HOMER software was used to simulate this system [2].

Design, Sizing, and Implementation of a PV System for Powering a Living Room. This paper is a design of a photovoltaic systems that powers a living room. A load estimation has been calculated based on both normal mode load operating and power saving mode. The paper shows the design equations for each component of the systems and shows the results of implementing it.

The components of the proposed photovoltaic system in this research paper are PV panels, charge controller, batteries, and the inverter. The ratings of each one of these components is based on the load estimation for the power consumption in saving mode.

The paper compares between the load power consumption between normal mode operation and saving power mode operation and based on the comparison the design was based on the saving mode power consumption to reduce the overall cost but still powers the loads as required. [3]

Analysis of backup power supply for unreliable grid using hybrid solar PV/diesel/biogas system. This paper proposed a hybrid PV/Diesel/Biogas backup power source for unreliable power grids. In this research a case study has been used from South-West Nigeria. Homer software has been used for the design in two different arrangements as two different systems. The first proposed system is Grid/PV/Biomass and the second proposed one is Grid/PV/Diesel. The paper includes an economical comparison between the two systems, and it shows that the Grid/PV/Biomass is the most economical choice for the used case study, and it is the mor environmentally friendly that the other proposal.

The study confirms that many areas struggle with unreliable utilities and in order to increase the reliability and have a stable electrical power source alternative power sources are required to backup the primary source which is the grid [4].

Stand-alone backup power system for electrical appliances with solar PV and grid options. this paper proposes a backup power system that is compatible with two different power sources. The fist source is the power grid which supplies AC power, and the second source is a PV solar system that supplies DC power. The system consists of a 300V rechargeable battery bank, with voltage matching concept used to maintain the battery bank fully charged. A bypass switch powered from the primary source (Grid) was used to transfer between the power source and battery bank to feed the loads when both primary (Grid) and secondary (PV) power sources are not available.

To prove the Voltage matching concept used in this proposed design MATLAB was used for simulation. The study confirms that the proposed systems can achieve about 99% power efficiency comparing to the traditional one which does not include the voltage matching concept.[5]

Optimizing Energy Cost via Battery Sizing in Residential PV/Battery Systems. This paper proposed a photovoltaic grid connected solar system design for a residential building. The purpose of the proposed system in this research is to decrease the electricity cost. Four different PV panels installation scenarios were proposed, the difference between the four scenarios is the distribution of the PV panels on the available area.

The paper shows a comparison between the four scenarios to eventually choose the most cost effective one which suggests distributing PV panels between the roof and the south façade of the residential house that used as a case study in Finland.[6]

Design and Implementation of a Low-Cost Solar PV Backup System for Low Reliability Grids. This paper proposed a design for a PV based back-up system for critical loads in areas with unreliable grids. In this paper an 8-bit microcontroller with simplified MPPT (Maximum Power Point Tracker) is used to pull the maximum available power from the PV array.

The control system used in the proposed design provides protection for the system components from fluctuations in the system that could be a result of an unplanned event such as a fault of a failure. It also controls the charge status for the battery bank which ensures longer battery life and increases the reliability of the system. [7]

Chapter 2: The Solar Energy Resource

2.1 Overview

The purpose of this chapter is to provide a brief introduction to solar renewable energy systems, how light from the sun becomes available to produce energy, and different types of solar energy systems. The chapter ends with brief explanation of photovoltaic system types and applications of each type.

2.2 Introduction

A clean energy revolution has been taking a place across the world in the last few years. For an energy resource to be reliable, it must deliver the service that the consumer expects. It must be available in the quantity desired when the consumer wishes to consume it and the resource must be available at a price that is economically affordable. Longer term, in addition to reliability there is another criterion for the energy resource that must be met which is environmental sustainability. Renewable energy is the energy generated from natural sources that do not have finite end. such as wind power, hydropower and solar power which is used in this project [8].

Solar intensity is more than 1 kW/m^2 outside the earth's atmosphere while the average daily interception on the earth's surface is 4 kWh/m^2. In less than 1 month, the solar energy intercepted by earth is equivalent to all the energy originally stored in the conventional energy resources of coal, petroleum, and natural gas on the planet [9]. This chapter reviews the two different types of solar energy systems, solar thermal systems, and photovoltaic systems.

2.3 Solar Energy Systems

When solar power absorbed by surface, it could be converted to electrical power energy directly or to thermal energy and then to electrical energy. Photovoltaic systems convert sunlight to electricity directly, while thermal solar systems collect and concentrate sunlight to generate high temperature that is high enough for electric power generation.

2.3.1 Solar Thermal Power Systems

The most obvious use of solar energy is for direct heating. As mentioned, solar thermal power generation systems collect and concentrate sunlight to produce high enough temperature to generate electricity.

All solar thermal power systems consist of collectors with reflectors and a receiver. Reflectors are mirrors that focus sunlight onto the receiver. In most solar thermal power systems high temperature is used to heat a circulated flued to produce steam, then the steam is converted to mechanical energy using turbines that power a generator to produce electricity [10].

There are three main types of solar thermal power systems, linear concentrating systems, solar power towers and solar dish/engine systems. Below is a brief explanation of each type.

Linear Concentrating Systems

Linear concentrating systems collect the sun's energy using long, rectangular, curved (U-shaped) mirrors. The mirrors focus sunlight onto receivers (tubes) that run the length of the mirrors. The concentrated sunlight heats a fluid flowing through the tubes. The fluid is sent to a heat exchanger to boil water in a conventional steam-turbine generator to produce electricity [11].

Solar Power Towers

A solar power tower system uses a large field of flat, sun-tracking mirrors called heliostats to reflect and concentrate sunlight onto a receiver on the top of a tower. Sunlight can be concentrated as much as 1,500 times. Some power towers use water as the heat-transfer fluid. Advanced designs are experimenting with molten nitrate salt because of its superior heat transfer and energy storage capabilities. The thermal energy-storage capability allows the system to produce electricity during cloudy weather or at night.

Solar Dish/Engine Systems

Solar dish/engine systems use a mirrored dish similar to a very large satellite dish. To reduce costs, the mirrored dish is usually composed of many smaller flat mirrors formed into a dish shape. The dish-shaped surface directs and concentrates sunlight onto a thermal receiver, which absorbs and collects the heat and transfers it to an engine generator [11].

2.3.2 Photovoltaic Systems

A photovoltaic cell (PV cell) converts sunlight energy to electrical energy using adaption of electrical semiconductors. A PV cell is designed to transfer energy in each individual photons entering the panel to electrons that are channeled into an external circuit to power an electrical load.

A PV panel consists of multiple PV cells connected together in an electrical circuit that can be connected to an external circuit. Since an individual PV panel has limited output compared to a typical residential or commercial load, a PV system is usually a combination of multiple panels to deliver the required electricity to power a certain load [9].

There are other systems for converting energy from the sun to electrical energy such as thermal solar systems, but PV systems are the most used method of generating electricity directly from the sun currently [9].

Photovoltaic systems configuration can be divided into three main configurations based on whether the system is connected to the grid or not, Gride-Tied, Off-Grid and Hybrid solar systems. Below is a brief explanation of each configuration.

Grid-Tied Solar Systems (On-Grid)

A Grid- Tied solar system is a PV system that is connected to the utility power grid. Unlike Off-Grid systems and Hybrid systems, Grid-tied systems do not need batteries and other stand-alone equipment, it basically uses the utility grid as a “virtual battery” which means no battery maintenance or replacement needed [8].

Components of a Grid-Tied Solar System:

Since the power generated from the photovoltaic system is DC and the generation varies based on the sun radiation on the photovoltaic panels the system needs a device to stabilize the DC output of the photovoltaic array (DC/DC converter) and an inverter

(DC/AC converter) to convert the output power from DC to AC to make it possible for the system to feed the grid which has AC power.

The basic components of a Grid-Tied solar system are solar array which is a group of solar panels, DC/DC converter and an Inverter. The system also would have protection and isolation devices such as circuit breakers and isolation switches.

Off- Grid Solar Systems (Standalone)

An Off-Grid solar system is a PV system that is not connected to the utility power grid. It requires battery storage and backup generator in order to ensure access to electricity all the time. The need of batteries makes the system less efficient than the Grid-Tied solar system due to the complications that comes with batteries adding that these battery banks need to be replaced every 10 years [8]. Due to the additional components needed for Off-Grid solar systems and the additional maintenance needed for the battery bank, the efficiency of Off-Grid solar systems is less that the efficiency of Grid -Tied solar systems. Off-Grid systems are typically used in remote areas where it is difficult and more expensive to have a connection from the grid.

Components of an OFF-Grid Solar Systems

Depending on the kind of loads fed by the system it might need an inverter or not. If the system is feeding only DC loads there will be no need to add an inverter to convert from DC to AC and the system would only need DC/DC converter and battery bank. But in case the system feeding AC loads the system will still need an inverter to convert the output power from DC to AC.

The basic components of an Off-Grid solar system that feeds AC loads are solar array, which is a group of solar panels, DC/DC converter, Inverter battery bank and a backup generator. The system also would have protection and isolation devices such as circuit breakers and isolation switches.

Hybrid Solar System

A hybrid solar system combines between the Gride-Tied and Off-Grid systems. It could be described as Off-Grid solar system with utility backup or a Grid-Tied solar system with extra battery storage. Unlike Off-Grid system, there is no need for a backup generator in this system, which makes it less expensive [8].

Components of a Hybrid Solar System

Since the power generated from the photovoltaic system is DC and the generation varies based on the sun radiation on the photovoltaic panels the system needs a device to stabilize the DC output of the photovoltaic array (DC/DC converter) and an inverter

(DC/AC converter) to convert the output power from DC to AC to make it possible for the system to feed the grid which has AC power. Batteries are needed in this system for backup in case of an outage during nighttime.

The basic components of a Hybrid solar system are solar array, which is a group of solar panels, DC/DC converter, Inverter, and a battery bank. The system also would have protection and isolation devices such as circuit breakers and isolation switches.

2.4 Power Electronics components used on Photovoltaic Systems

Power electronics is the application of electronics to the control and conversion of electric power. In previous section DC/DC converters and Inverters were mentioned as components of photovoltaic systems. This section is a short introduction to these two components.

DC/DC Converters.

DC/DC converters provide regulated DC voltage level from unregulated DC voltage level. There are different types of DC/DC converters and in this section Buck converter, Boost converter and Buck-Boost converter will be briefly discussed.

Buck converter

A buck converter is a DC step down converter. It steps down the input to the required output and it typically consists of two switches, a transistor and a diode, an inductor and capacitor. Filters made of capacitors are normally added to this type of converters to reduce the voltage ripples [12].

Boost converter

A boost converter is a DC step up converter. It steps the input up to the required output, so the output voltage would be greater than the input voltage. This converter consists of at least two semiconductor switches (A diode and a transistor) and at least one energy storge element (A capacitor, inductor, or a combination of both). For this converter filters made of capacitors will also need to be added to reduce voltage ripples [13]. In this proposed design a boost converter is used to boost the input DC voltage to the inverter.

Buck-Booster converter

A Buck-Booster converter would have an output voltage that is either greater or less than the input voltage. The basic principles of the inverting buck-boost converter are while in the on state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. in this state capacitor supplies energy to the output load. While in the off state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R [14].

Inverters

An Inverter converts DC input to AC output. Inverters could be voltage source inverters and current source inverters. Voltage source inverters (VSIs) independently controlled output is a voltage waveform. Similarly, current source inverters (CSIs) are distinct in that the controlled AC output is a current waveform [15].

The conversion from DC to AC is a result of power switching devices, which are commonly fully controlled semiconductor power switches. The output waveforms are therefore made up of discrete values, producing fast transitions rather than smooth ones. The ability to produce near sinusoidal waveforms around the fundamental frequency is dictated by the modulation technique controlling when, and for how long, the power valves are on and off. Common modulation techniques include the carrier-based technique, or pulse width modulation, space-vector technique, and the selective-harmonic technique [16].

Chapter 3: Power Substations

3.1 Overview

This chapter focuses on power substation, a general introduction to power substations that explains the relationship between a substation and the whole power system, types of power substations (distribution, transmission, and switching substations), and the main components of a power substation.

3.2 Introduction to Power Substations

A traditional electric power system starts from generation then transmission and ends with distribution. Power generation occur in power plants then the power gets transmitted in transmission lines and finally distributed in multiple stages to reach the consumers (Loads) weather industrial commercial or residential.

During the power flow from generation to distribution many components make the power system and such as power substations, which could be switching substations, transmission substations or distribution substations.

When power is generated, voltage needs to be stepped up before transmission to reduce current which reduces losses and the amount of used materials in transmission lines, then the voltage gets stepped down in multiple stages to reach the voltage level required to feed loads and this flow has to be monitored and controlled to provide protection for the system components. Substations are the parts of the power system where voltage gets stepped up or down and where protection control and monitoring devices are in the power system [17].

3.3 Types of Power Substations

This section focuses to the different categories of power substations based on the substation function and location in the power system. In general, a power substation can be a Transmission Substation, Distribution Substation, Switching Substation (Switchyard) or any combination of these three categories [18].

Some references categorize power substations as Switching substations, Customer substations, system substations and distribution substations. Switching substations are the substations that connect the power plant to the grid Customer substations function as power source for specific business customers, System substations are basically switching and transmission substations, and Distribution substations are the substations used to supply power to most customers. There are other classifications for the types of power substations, but in this section, we will follow the categories mentioned in the previous paragraph.

3.3.1Transmission Substation

In transmission substations voltage gets stepped down from transmission voltage level to sub transmission voltage level to then distribute the power on distribution substations. Transmission substations consists of switching equipment, controlling and monitoring devices, and power transformers.

3.3.2 Distribution Substations

In Distribution substations voltage gets stepped down voltage from sub-transmission level to distribution level for residential, commercial and industrial loads. A distribution substation also consists of switching, controlling and voltage step-down equipment.

3.3.3 Switching Substation

The purpose switching substations is to provide circuit protection and switching flexibility. A switching substation consists of switching, controlling, and monitoring devices. Reliable switching in transmission system maintains reliable service under abnormal conditions or maintenance. Switching substations do not have power transformers [18].

3.4 Power Substations Components

This section focuses on power substations components in general.

Power Transformers

A transformer is used to step voltage up or down based on the application it's used for. Power transformers are part of the power transmission system. They typically have a high power rating and exist in a substation yard. Power transformers are critical components in the system, which leads them to require special protection.

Instruments Transformers

Instruments transformers are current transformers (CT's) and potential transformers (PT's) that used to step down the current and voltage for protection and monitoring devices. Theses transformers do not power devices, they are used only for metering and insulation which provides safety for personnel using them.

Circuit-Breakers

A circuit breaker is a protection device that provides mechanical switching to open and close the circuit when needed. Circuit breakers are controlled by controlling devices such as relays to open or close the circuit within a specific time in case of an abnormal condition to protect the equipment in the power system [19]. Circuit breakers can be in the substation yard or in the substation control house. There are different types of circuit breakers and different insulation materials used in them.

Lightning and Surge Arrester

Lightening and Arresters are devices that typically exist in the substation yard used to protect the system equipment from high voltage that occurs as a result of lightning strikes, switching, faults and any other case of transient voltage. Lightening and surge arresters are installed in critical points where they are connected directly to ground to deflect transient voltage harmlessly.

Wave Trap

Wave Traps are low pass filters, used to protect the system from signals with high frequency that are used for communication circuits, since substation equipment are designed to work on either 50 Hz or 60Hz frequencies.

Bus Bar

A bus bar is a metallic bar (conductor) that is used for collecting power from feeders interring the substation and distributing it to outgoing feeders from the substation. It's typically made of cupper or aluminum, and it could have different shapes such as rectangular, cross sectional and round.

Isolator in Substation

An Isolator in a substation is a switching device, used to isolate part of the system for maintenance purposes. Isolators would typically exist on circuit breakers ends, lines, bus bars and any other component in the system that would need to be isolated for maintenance or other purposes.

Relay

A relay is a protection and monitoring device it typically exists in the control house of a substation, to monitor the system (Current, voltage, power) and detects abnormal conditions in the system. Relays control circuit breakers by sending signals to the breakers to open in case of a fault or another abnormal condition.

Batteries

Batteries typically exist in the control house of a substation to feed critical components in the substation such as relays, operation lighting, control circuits and UPS's (Uninterruptible Power Sources). Batteries are part of the DC auxiliary system in a substation which mentioned below.

3.5 Auxiliary AC/DC Power Systems

Many of the substation components mentioned above need to be fed by a low voltage source, either AC or DC. The Auxiliary AC/DC Power systems are typically fed from an auxiliary power transformer.

Auxiliary AC System

AC auxiliary systems in a power substation is used to feed AC loads such as lighting, outdoor device heaters, UPS's (Uninterruptible power sources), AC motors for different substation components and battery chargers.

The main components of the AC system are station light, Automatic and manual transfer switches, AC cabinets, and cabling and wiring.

Auxiliary DC System

A power substation could have one or more DC systems, based on the number of voltage levels needed. Voltage levels needed for most DC auxiliary systems could be either 110V or 220V, but some systems such as telecommunication devices require lower voltage. If the power consumption for these devises is low enough, then choppers (DC/DC converters) can be used instead of having DC system.

The main components of a DC auxiliary system are batteries, battery chargers, battery fuse boxes and distribution switchboard including the DC monitoring relay.

A DC system in a power substation is typically used to power circuit breaker trip coils, indicating lights, relay protection control circuits, alarm circuits, and DC motors for substation equipment. Which makes it extremely important to always have an available reliable energy supply for the substation reliable and safe operation [20].

Chapter 4 System Design & Simulation

4.1 Overview

This chapter contains the design of a PV system that works as a backup power source for the primary power source (Grid) to feed a Protection, Control, and Monitoring (PCM) system in a power substation. This proposed system consists of solar array, isolation switches, circuit breakers, inverter, and an automatic transfer switch. The project has been simulated using MATLAB/Simulink.

As mentioned in previous chapters, the DC auxiliary supply system in a substation consists of batteries and a battery charger operating on 130 V or 240 V to feed Protection Control and Monitoring system. An auxiliary transformer feeds an Ac panel which feeds the battery charger with other different AC loads in the substation. Then the battery charger feeds both the PCM loads and batteries. Below is a scheme for an existing DC auxiliary system that feeds a PCM system.

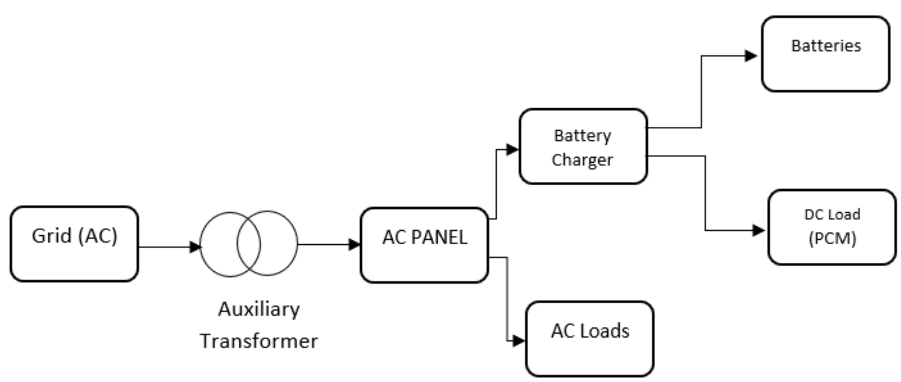

Fig 4.1: Existing Scheme of an Auxiliary DC System

The proposed PV based system

The proposed system in this thesis will have PV panels (PV Array) that generate DC power, inverter to convert the PV panels output from DC to AC, AC panel, automatic transfer switch to select and transfer the power source between the grid and the solar PV system, battery charger and batteries. Below is a scheme for the proposed system.

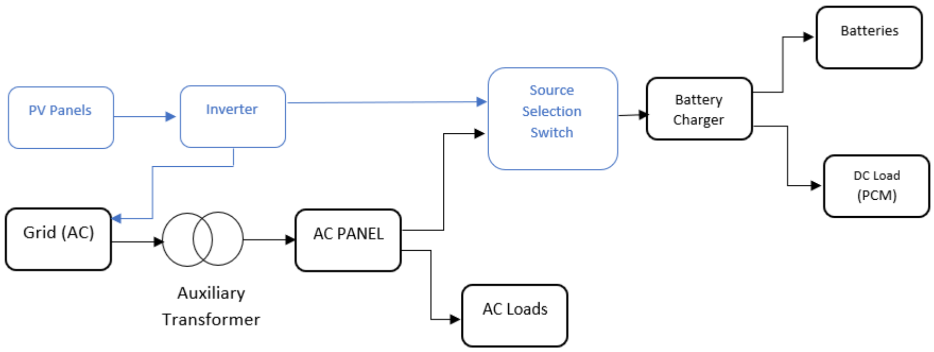

Figure 4.2: The Proposed Scheme for the DC Auxiliary System with PV Backup

System Components

Below are the components of the designed system. Some parts such as the batteries, battery charger and DC panel already exist in the system (In a substation). The added (Designed) components will be PV panels that generate DC power, Inverter that converts generated power from DC to AC, a source selection switch which selects between the inverter output and the auxiliary transformer output and protection devises for the PV systems such as DC isolator and DC circuit breaker.

Batteries and Battery Charger:

As mentioned previously batteries and battery charger in a substation make the auxiliary DC system. The proposed PV solar system is designed to be a backup for the grid to feed the battery charger that feeds batteries. With that said the PV array will be designed based on the rating of existing batteries and then feed an inverter which will feed the battery charger. Assuming the design is for battery capacity of 142 Ah, 0.5 efficiency and 0.8 depth of discharge. Equation (4.1) [3] below will be used estimate the daily power consumption based on the assumed battery capacity.

$$C(Ah) = \frac{Daily\ Power\ Consumption}{DoD \times EFF \times V} \qquad 4.1$$

Where:

C: The capacity of the battery.

Daily Power Consumption: The power consumed by the PCM.

DoD: The battery’s depth of discharge.

EFF: Battery’s efficiency.

V: The nominal voltage of the load.

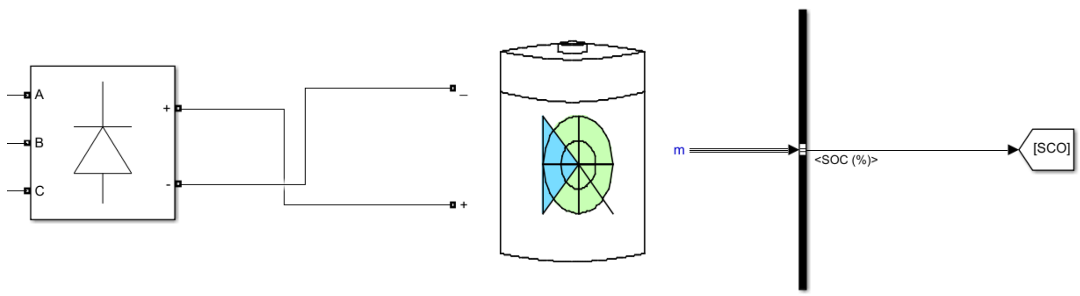

Figure 4.3: Simulink Module Battery and Battery Charger

Figure 4.3 above shows the battery with a rectifier as a battery charger in the Simulink module. A rectifier is used above to convert AC power to DC power to charge the battery. On the right side of the figure there is a “GOTO” block that is used to view the State of Charge for the battery.

PV array model:

A PV array is a combination of a number of PV panels which consist of multiple photovoltaic cells, that are designed to transfer the energy contained in an individual photon penetrating the panel to electrons that are channeled into an external circuit for powering an electrical load which is in this case the battery charger which feeds the PCM system.

The output power of a PV array depends on the daily power consumption and the sun peak hours as shown in equation 4.2 below [03]. The Sun Peak Hours are where the intensity of solar irradiance reaches an average of 1,000 W per hour per square meter.

$$P_{PV} = \frac{Daily\ Power\ Consumption}{Sun\ Peak\ Hours} \qquad 4.2$$

Where:

P_{PV}: The PV output Power.

Daily Power Consumption: The power consumed by the load daily in KW.

Sun Peak Hours: The number of hours where the intensity of solar irradiance reaches an average of 1,000 W per hour per square meter

In this case since this PV array is designed to feed the DC auxiliary system in a substation, the daily power consumption has been calculated based on the battery bank capacity using equation 4.1 where DoD is the Depth of Discharge, EFF is the battery bank efficiency and V is the load voltage.

Per Equation 4.1,

$Daily\ Power\ Consumption = C\ \times (DoD\ \times EFF\ \times V)$

The Battery Bank capacity that is used for the proposed design is 142 Ah, with 80% depth of discharge and 50% efficiency. Substituting in equation 4.1

$Daily\ Power\ Consumption = 142\ Ah\ \times (0.8\ \times 0.5\ \times 125)$ = 7.100 KWh

The calculated daily power consumption is to be used for PV panel sizing, assuming that the Sun Peak Hours Is 5 hours. Using equation 4.2

$P_{PV} = \frac{7.100}{5}$ = 1.420 KW

= 1420W

The number of needed PV panels to generate the calculated power can be found by dividing the power on a panel's power as shown in equation 4.3 [03] .

$$Number\ of\ Panels = \frac{P_{PV}}{Nominal\ PV\ panel\ Power} \quad 4.3$$

Where:

P_{PV}: The calculated total needed PV power to feed the load

Nominal PV panel Power: The output power of each PV panel, which is specified by the manufacturer and found in the panel's data sheet.

Choosing REC Solar REC400AA-PURE PV panel with the following specifications:

- Nominal Power: 400 Watts
- Watt Class Sorting: -0/+5
- Vmp: 42.1 Volts
- Imp: 9.51 Amps
- Voc: 48.8 Volts
- Isc: 10.25 Amps
- Panel Efficiency: 21.6%

Substituting in equation 4.3 to find how many panels are needed to generate at least 1420 W.

$Number\ of\ Panels = \frac{1420W}{400\ W}$ = 3.55 Panels

Since 3.55 is not a whole number, the next higher whole number is to be chosen, which is 4 panels. Now that the number of panels is known, the Max output of the PV array can be calculated to be used in choosing the Inverter and isolation devices. Figure 4.4 below shows the PV array module used in the Simulink design.

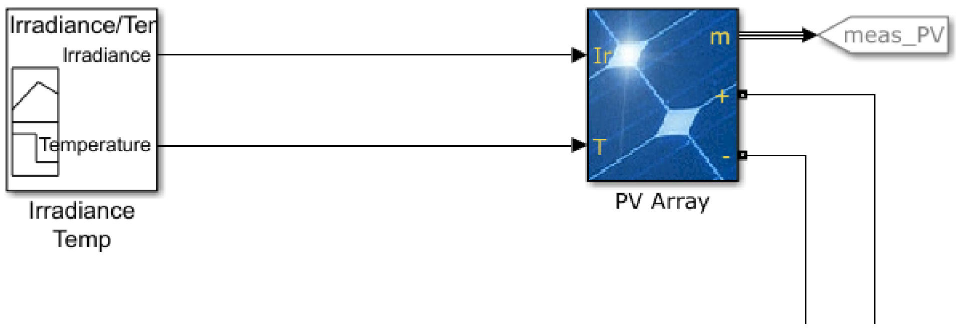

Figure 4.4: The Simulink Module PV Array

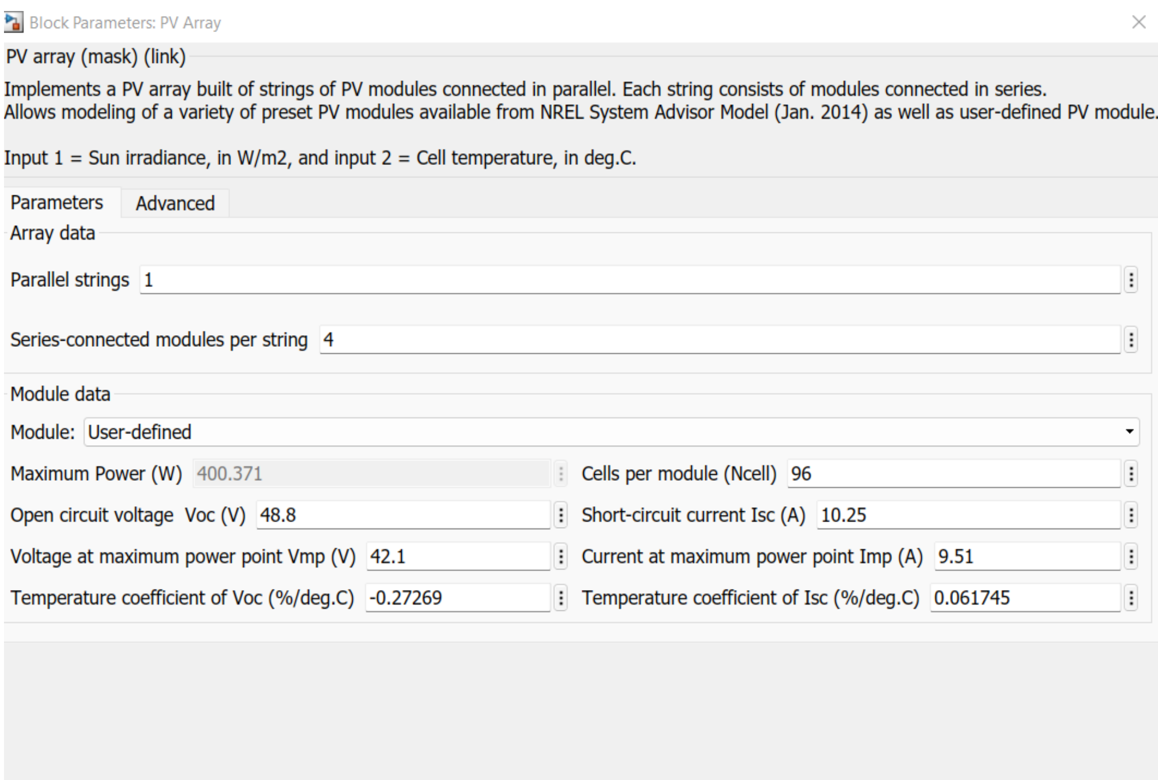

Figure 4.5: PV Array Parameters

Figure 4.4 shows the PV with two inputs, the Irradiance which is a Ramp-up/down signal and the temperature. The irradiance varies from 200 to 1000 W/m^2 and the temperature varies from 20 to 50 C°.   while figure 4.5 shows the PV modules number, connection (4 modules connected on series) and the parameters proposed in the section above (Maximum power, Open circuit voltage, short circuit current, voltage and current at maximum power point).

4.2 DC to AC inverter

Inverter:

As mentioned previously the inverter converts DC power generated by the PV array to AC power, to feed the battery charger and the power grid when there is no need to feed the charger or when there is an excessive power generation. The selection of an inverter is based on the PV output which is the input of the inverter and the AC load voltage which is the battery charger input voltage. The inverter must be sized with a rated power that is larger than the maximum output of the PV panels, a maximum DC input voltage that is higher than the total open circuit voltage of the PV array and a maximum input current that is higher than the PV array short circuit current. To calculate the maximum power generated from the PV panels, the number of panels is to be multiplied by the power generated by each panel as shown below in equation 4.4.

$$P_{Max} = \text{Nominal Power of a PV Panel} * \text{Number of panels} \qquad 4.4$$

Where:

P_{Max}: The maximum power generated from the PV array.

Substituting in 4.4:

$P_{Max} = 400\text{V} * 4$

= 1.6 KW = 1600 W

To calculate the PV array open circuit DC voltage (V_{OC}) the open circuit voltage for the used PV panel is to be multiplied by the number of panels as shown in equation 4.5.

$$PV\ Array\ V_{out}(series) = V_{OC} \times Number\ of\ PV\ Panels \quad 4.5$$

Where:

$PV\ Array\ V_{out}(series)$: The PV array open circuit DC voltage.

V_{OC}: The open circuit DC voltage per PV panel.

Substituting in 4.5:

$$PV\ Array\ V_{out}(series) = 48.8 \times 4$$

$$= 195.2$$

The inverter is to be chosen with a Max Power Array Power (W_P) greater than maximum PV Power (P_{Max}) which is 1600, A maximum input voltage greater than 195.2 V and a maximum input current greater than 10.25 A

Max Power (W_P) > 1600 W

Max V_{DC} input > 195.2 V

Max Input Current > 10.25 A

Choosing OutBack Power Inverter 5,000W **(**SBX5048-120/240 SkyBox) with the following specifications:

- AC Voltage: 120/240V split- phase
- AC Frequency: 60 Hz
- Max Continuous AC Output Power: 5,000 VA (Volt-Amps)
- Max Continuous Output Current (@240V): 24 Amps @ 25 ℃
- Power Factor at Rated Power: 1
- Max PV System Voltage: 600V
- PV Input Voltage Range: 200V - 600V
- MPPT Voltage Range: 250V - 600V
- Max Input Current: 20 Amps
- Max Short Circuit Current: 32 Amps
- Typical Inverter Efficiency: 97%

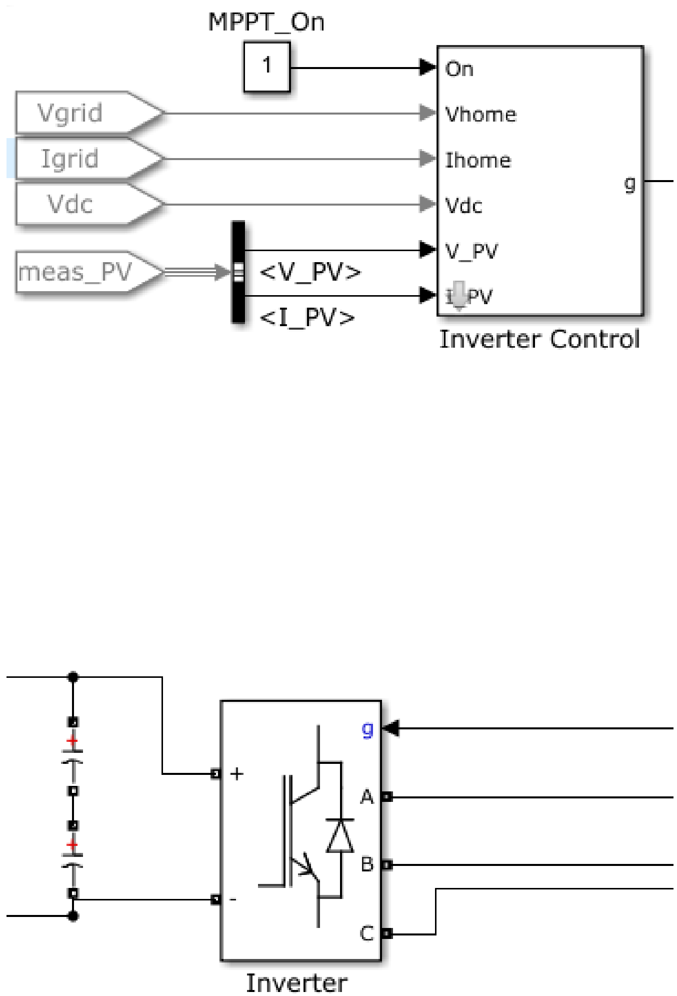

Figure 4.6: Inverter and Inverter Controller.

Figure 4.6 above shows the used IGBT/Diodes inverter connected with capacitors to filter the signal and with a controller that works as a power point tracker system (MPPT), DC regulator to regulate the PV array DC output, a Current regulator and a PWM modulator.

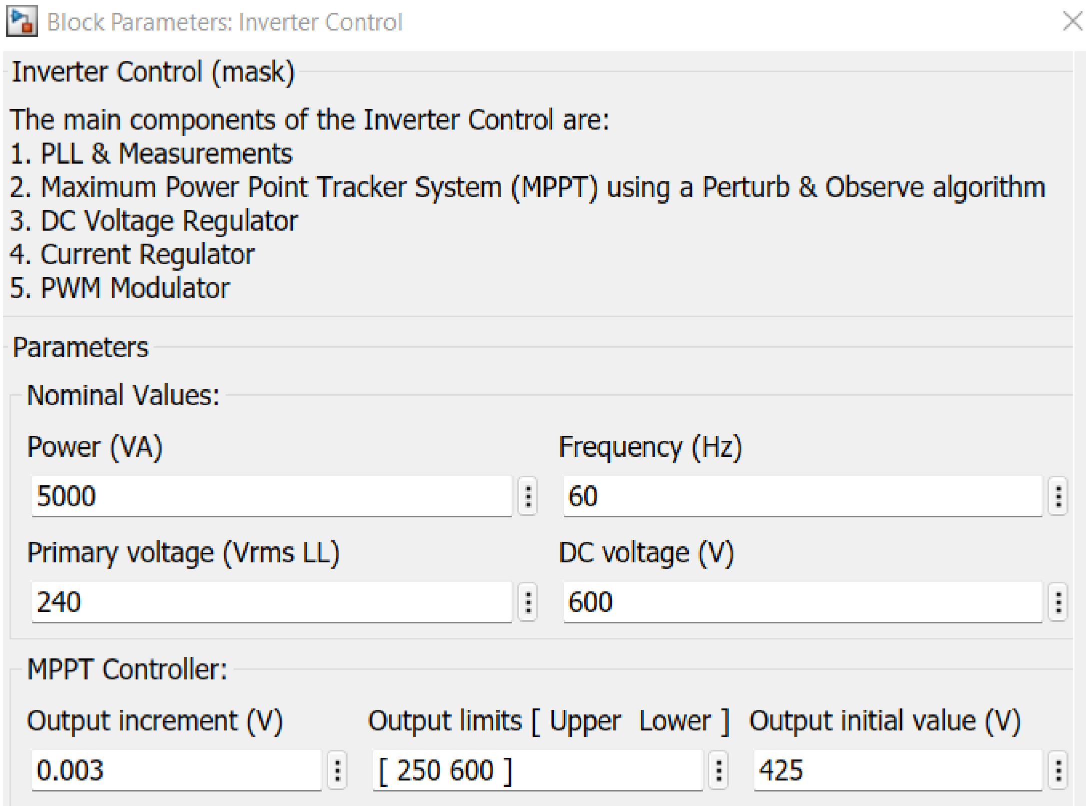

Figure 4.7: Inverter Controller Parameters

Figure 4.7 above shows the Inverter Controller parameters, which matches the Inverter ratings that was proposed in the section above.

Source Selection Switch/Automatic Transfer Switch (ATS):

A source selection switch or an Automatic Transfer Switch is the device which switches between power sources. The inputs for the Source Selection Switch are the grid and the PV array output. To keep the system reliable the source selection switch will transfer between sources as needed. A source selection switch was not part of the Simulink module.

Choosing W2R-3P Automatic Transfer Switch (ATS)for PV with the following specifications:

• Rated current le A	16、20、25、32、40、50、63	100	
• Insulation voltage Ui	AC 690V		
• Rated voltage Ue	AC 400V		
• Grade	Grade PC: able to male and withstand, not to break short-circuit current		
• Use category	AC-33iB		
• Pole	2P	3P	4p
• weight(kg)	0.62	0.72	0.81
• Life	Electrical: 2000times; Mechanical:5000times		
• Rated conditional short-circuit current lq	50kA		
• SCPD (fuse)	RT16-00-63A		
• Rated impulse withstand voltage	8kV		
• Control circuit	Rated control voltage Us: AC220V,50Hz Correct working condition85%Us~110%Us		
• Auxiliary circuit	AC220V/AC110V 50/60Hz		
• Contact transfer time	<50ms		
• Operating transfer time	<50ms		
• Return transfer time	<50ms		
• off-time	<50ms		
• Temperature range	-5℃~+40℃ average temperature not more than 35℃ in 24 hours		

Protection Devices

Protection and isolation devices are to be added to the system for protection and maintenance purposes. In our system a DC isolator and a circuit breaker are installed between the PV array and the inverter, used to isolate the PV array for maintenance purposes and to protect it in case a fault occurs on the system. Then there is an AC circuit breaker installed after the inverter to also to isolate the inverter for maintenance or protection.

4.3 MATLAB/SIMULINK System Level Simulation

This section shows the MATLAB/Simulink simulation for the project, which consists of PV array with two inputs, the Irradiance (W/m^2) and the temperature in C, inverter with a controller that boosts the DC input by MPPT and regulates the DC input voltage, capacitor bank to filter the inverter's harmonics. Figure 4.8 bellow shows the wiring diagram of the system with the components.

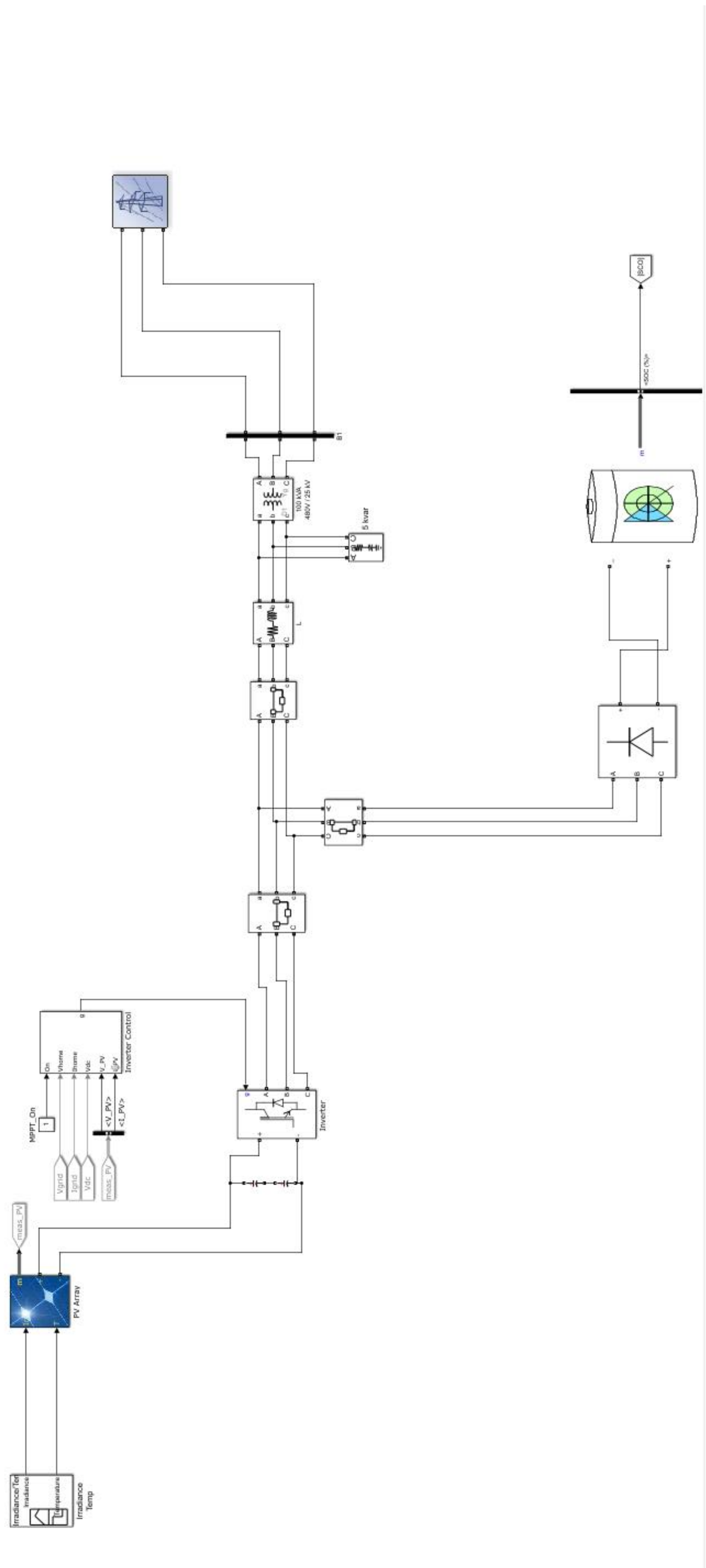

Figure 4.8: Wiring Diagram of The Design

The SIMULINK wiring diagram in figure 4.8 shows the whole system, starting from the PV array, inverter with a controller, capacitor bank filter for the inverter, circuit breaker to isolate the PV system, a diode bridge used as a battery charger to charge the battery, a circuit breaker to isolate the grid, transmission line, a 5 kvar load on the grid, a transformer and electric grid (Primary Source).

Figure 4.4 below shows PV Current, voltage, and diode voltage.

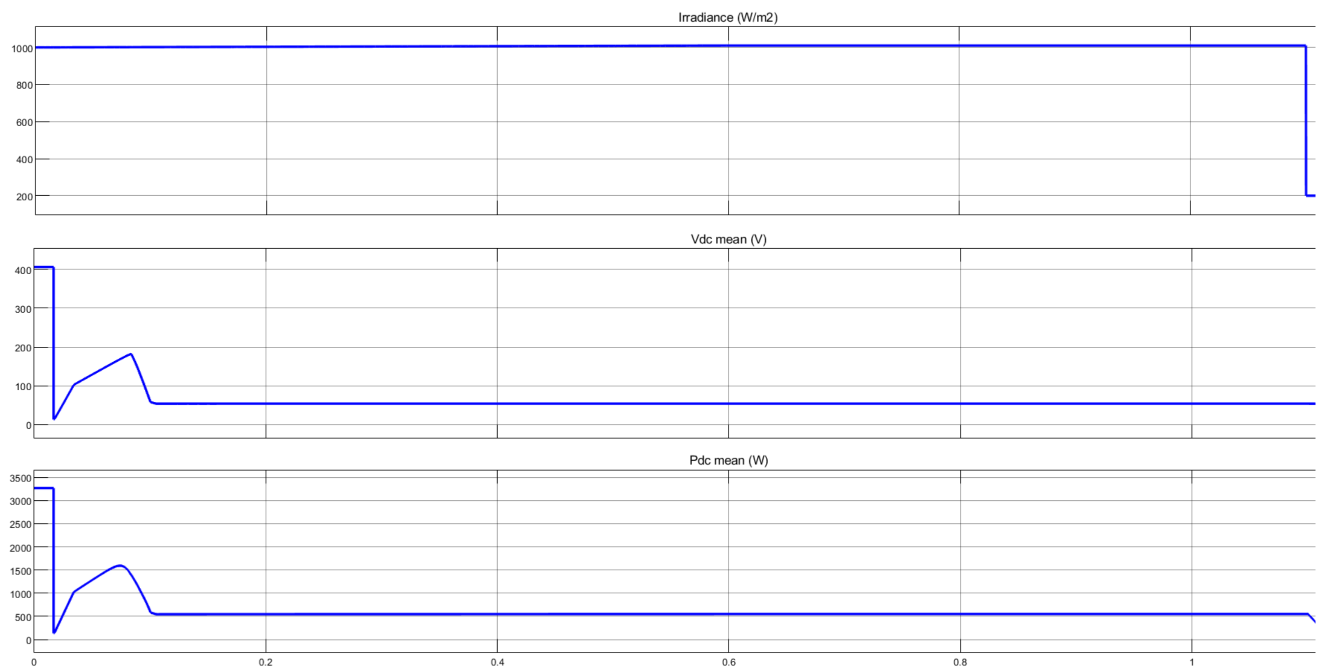

Figure 4.9: PV Irradiance Input, DC Voltage and DC Power Mean

Figure 4.9 above shows the signals for the PV array parameters, the Irradiance (Ir) (W/m^2) input, DC voltage mean and the DC power mean.

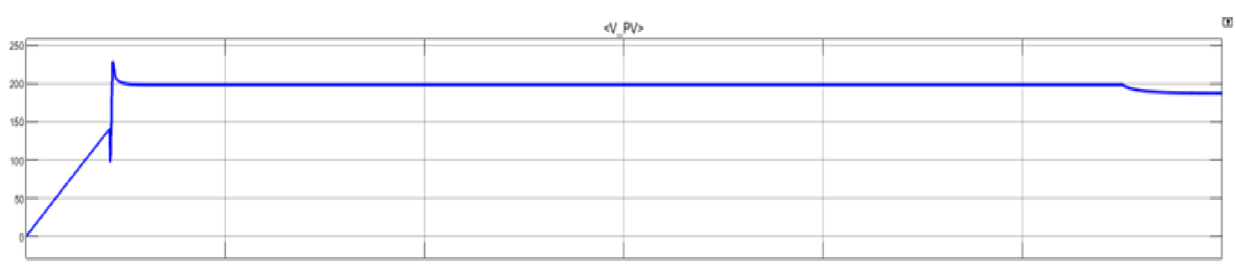

Figure 4.10: PV Array DC Voltage

Figure 4.10 shows the PV array DC output voltage before boosting it.

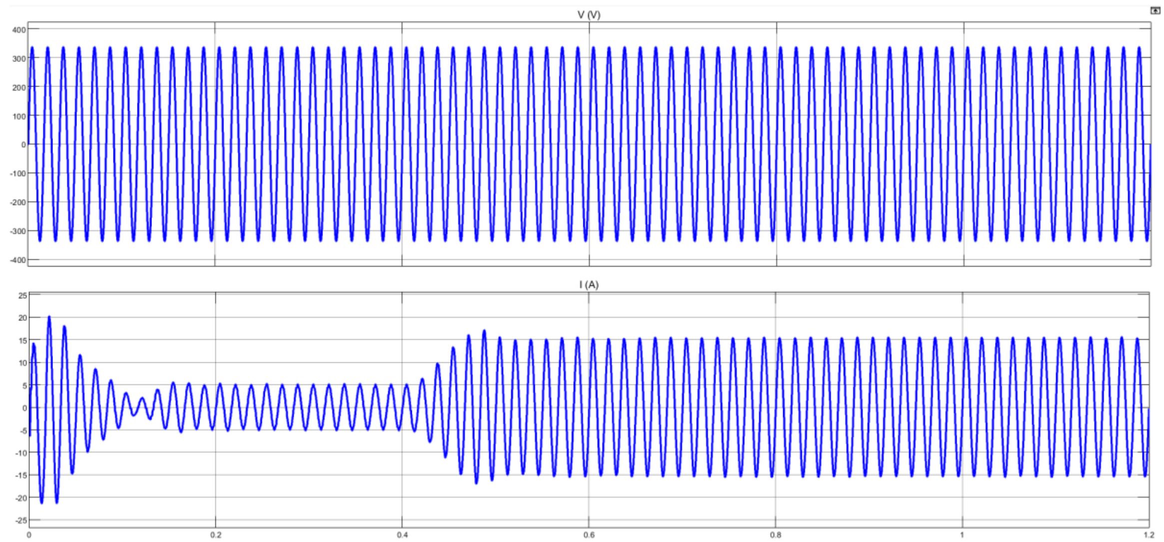

Fig 4.11: The inverter's Voltage and Current Output

Figure 4.11 shows the output voltage and current of the inverter. The inverter controller boosts the DC input (PV array output) and the inverter converts it to AC as shown in the figure.

Figure 4.12 shows the battery's State of Charge (SOC) increasing which is fed from the PV system.

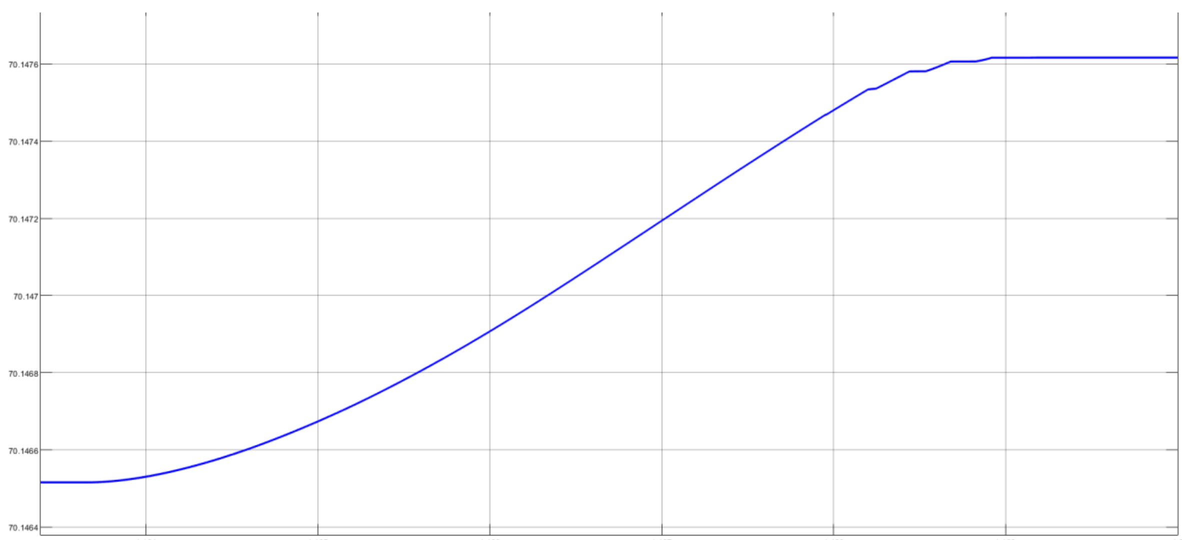

Figure 4.12: Battery State of Charge

Figure 4.11 shows the change in the state of charge for the battery. The original state of charge (SOC) is 70% then by feeding the battery from the PV system it starts increasing. The increase in the state of charge here is slow because of the losses due to using a diode bridge rectifier instead of a battery charger in the simulation.

Chapter 5 Conclusion

5.1 Conclusion

Protection, Control and monitoring device's reliability and efficiency are extremely important to protect the system components and since most PCM systems are fed from the DC auxiliary system in a substation which is fed from the grid, the reliability of the PCM system depends on the reliability of the grid. Unplanned events can happen anytime and anywhere and could last for long time which makes it very important to have a backup reliable power source to feed the critical components in a substation such as the proposed PV system.

This thesis proposed a design for a Grid-tied PV system with minimum components and it was simulated using MATLAB/Simulink. Grid-tied photovoltaic (PV) system is a great option to have as a backup power source for an auxiliary DC system in a power substation. It's reliable, renewable, and environmentally friendly. Power electronics components (which are part of the PV system) generate harmonics that affect the power quality which affects the system components negatively. Adding filters to the system is extremely important to minimize the effect of these harmonics.

Adding additional components to the power system is always associated with a certain risk level and additional maintenance cost. Before adding a backup solar system to a substation, a risk evaluation study must be done, including the reliability factor of the primary power source. Further studies could apply this design on a specific case study and include an economical study with a risk evaluation.

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