CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Real-time Fault Detection System For Large Scale Grid-Integrated Solar Photovoltaic Power Plants

by

Muhammad Saad Iqbal

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Electrical Engineering

2019

I dedicate this work to my parents for their limitless love, care and inspiration.

CERTIFICATE OF APPROVAL

Real-time Fault Detection System For Large Scale Grid-Integrated Solar Photovoltaic Power Plants

by

Muhammad Saad Iqbal

(MEE171025)

THESIS EXAMINING COMMITTEE

S. No.	Examiner	Name	Organization
(a)	External Examiner	Dr. Syed Ali Abbas Kazmi	NUST, Islamabad
(b)	Internal Examiner	Dr. Muhammad Ashraf	CUST, Islamabad
(c)	Supervisor	Dr. Umer Amir Khan	CUST, Islamabad

Dr. Umer Amir Khan
Thesis Supervisor
May, 2019

Dr. Noor Muhammad Khan
Head
Dept. of Electrical Engineering
May, 2019

Dr. Imtiaz Ahmed Taj
Dean
Faculty of Engineering
May, 2019

Author's Declaration

I, **Muhammad Saad Iqbal** hereby state that my MS thesis titled "**Real-time Fault Detection System For Large Scale Grid-Integrated Solar Photo-voltaic Power Plants**" is my own work and has not been submitted previously by me for taking any degree from Capital University of Science and Technology, Islamabad or anywhere else in the country/abroad.

At any time if my statement is found to be incorrect even after my graduation, the University has the right to withdraw my MS Degree.

(Muhammad Saad Iqbal)

Registration No: MEE171025

Plagiarism Undertaking

I solemnly declare that research work presented in this thesis titled "*Real-time Fault Detection System For Large Scale Grid-Integrated Solar Photovoltaic Power Plants*" is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been dully acknowledged and that complete thesis has been written by me.

I understand the zero tolerance policy of the HEC and Capital University of Science and Technology towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS Degree, the University reserves the right to withdraw/revoke my MS degree and that HEC and the University have the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized work.

(Muhammad Saad Iqbal)

Registration No: MEE171025

Acknowledgements

I hereby thank Allah Almighty to whom we belong and to whom we shall return and by his blessings we are able to contribute our part in betterment and growth of the world of science and engineering. I am thankful and greatly indebted to my teacher and supervisor **Dr. Umer Amir Khan**, without whom this work could not have been done. His guidance throughout my thesis has been a great help in moving to the right direction. His sincere advices, directives and constructive criticism on my work have helped me bring out this study to a conclusion. I would also like to express my gratitude to Messrs Wah Nobel Group of Companies who have allowed me to conduct my study on their PV power plant. I am also thankful to my parents who have been a source of encouragement and motivation throughout my life and especially for this work.

(Muhammad Saad Iqbal)

Registration No: MEE171025

Abstract

The global solar photovoltaic (PV) installations are increasing rapidly in an effort to slow down the process of global warming and climate change. The clean and green energy from solar PV power plants is being utilized at every level from utility scale to distributed generation applications. The large scale PV plants are normally installed in grid-tied topology because of its simple and easy to install and operate design. As the size of grid-tied PV power plants increases, the probability of error occurrence also increases. When a small PV plant is installed on the rooftop of a house it is much easier to trace a fault and get the system back on track, however, as the sizes of PV plants grow the string sizes increase in PV arrays and it becomes a cumbersome and tiring activity to find the nature and location of the fault.

In this study, an algorithm with system for fault detection and identification is presented which is able to sense the abnormality in the DC power output and identify the fault in the DC side of PV power plant. The algorithm proposes mathematical operations which use basic statistical tools of mean and standard deviation to formulate the fault detection mechanism. Additionally, string power ratio is used to detect fault at the maximum power point tracking (MPPT) unit.

In order to implement and test the proposed fault detection system for large scale grid-integrated PV plants, a simulation model of PV system is developed in MATLAB Simulink based on 125 kWp grid-tied PV power plant installed at Wah Nobel Group of Companies, Wah Cantt., Pakistan. The modeled PV plant is configured such that it is able to very closely match its DC power output to that of reference PV plant. Different faults have been studied which can cause reduction in energy yield of PV plants. The study discusses and keeps its focus on the faults of faulty PV modules in a string, single or multiple strings failure, MPPT unit failure, partial shading on a PV string and soiling on a PV string.

Weather conditions, irradiance and PV module temperature, are obtained from the reference PV plant for several days and simulations are conducted to test the performance of proposed fault detection system. The results obtained from tests show that the proposed fault detection and identification system is able to detect an abnormal event in the PV system and accurately identify the nature of fault as well.

Contents

List of Figures

List of Tables

Abbreviations

AC	Alternating Current
a-Si	Amorphous Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DC	Direct Current
GW	Giga Watts
IGBT	Insulated-Gate Bipolar Transistor
kW	Kilo Watts
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MW	Mega Watts
PV	Photovoltaic
STC	Standard Test Conditions
VSC	Voltage Source Converter

Chapter 1

Introduction

1.1 Introduction

The study on real-time fault detection system for large scale solar photovoltaic power plants has been conducted and presented. The main purpose of this thesis is to understand the functioning of grid-tied solar PV plants, identify the faults which can be potential hurdle in achieving high yield and develop a fault detection mechanism for timely indication of the fault alarm. The alarm indication enables the PV power plant operator to act upon the fault indication and take necessary measures as per the nature of the fault.

This study presents a comprehensive discussion on several presently available fault detection algorithms, their pros and cons are also discussed. It is noticed that most of the proposed fault detection systems mentioned in Chapter 2 are formulated while considering very small sized PV plants. Further these algorithms are not tested on PV plants which are beyond 100 kW size. Today, PV power plants are being installed which are in capacities of mega watts and giga watts. So a need is felt that there should be a fault detection system which is designed by focusing large scale PV plants. This study terms the large scale PV power plant to such solar photovoltaic power plants which have installed capacity equal to or more than 100 kW. Below this size are referred as small scale PV power plants.

Implementation and testing of fault indication mechanism should be performed on large sized power plants. This will facilitate the power plant operators to have better picture of how the power plants are performing.

This study takes a 125 kW on-grid PV power plant as the reference power plant and models this PV plant for simulation on MATLAB®. The modeling and simulation helps understanding the performance deviations in presence of a certain fault. Two identical PV plants are modeled and names as Actual PV Plant and Theoretical PV Plant. Further the primary objective this study achieves is the development and implementation of a complete fault detection system which works in real-time environment and provides alarms whenever a fault occurs at the DC side of the PV plant.

The fault detection system is simple, easy to implement and robust as it has been tested under several conditions. The proposed system is equipped with a fault detection algorithm. This algorithm compares the power outputs of Actual PV Plant and Theoretical PV Plant using mathematical equations. These mathematical equations are developed with basic statistical tools of mean and standard deviation. The algorithm performs its computations and gives indications whenever a fault is occurred. For ease of operation, a GUI is created which helps in inducing faults at various times to the Actual PV Plant and also gives outputs of DC power and voltage of PV array, AC voltage from the inverter and fault alarms.

It is concluded from the study that the proposed real-time fault detection system has performed satisfactorily under several conditions. Further, future work is also recommended in the concluding chapter.

1.2 Background

Energy is the soul of today's human progress. Global energy consumption has increased drastically to meet the needs and uplift human living standards. Through the decades we have relied on fossil fuels to generate energy. The bad side that came with this necessity was the climate change. The carbon emissions from industries, power plants and transportations are leading to a point that could be the catastrophic end of human race. The modern living practices require huge amount of energy that gives increase to global warming. On the other side, fossil fuels are depleting which are the main source of energy generation. Either way, it is seen that alternatives are to be explored on urgent basis. Electricity generating fuel or coal based thermal power plants are considered one of the major carbon emitting sources and alternatively solar energy, wind energy, tidal and geothermal energy have come in to focus. It has taken several years to understand the need and now the power industry is moving towards these renewable sources and a few large scale deployments in capacities of mega watts can be seen today. The International Energy Agency (IEA) provide the statistics for the year 2018 in their annual 'Key World Energy Statistics 2018' that the said renewable energy sources are now providing for 1.7% of global demand compared to 0.1% in year 1973 [1]. The progress seems slow but the success is that the humans have understood the dire consequences if they do not take action now.

Among the rest of renewable energy sources, solar photovoltaic energy finds a strong place. Both the solar PV and concentration solar thermal power plants are increasing. The easy to install, scalable and flexible design of the solar PV power plants has brought this technology to domestic level as well. The net-metering provision as initiated by countries like Germany has enabled the domestic consumers to contribute their part. Now the domestic consumers are generating their own electricity and feeding the surplus to the grid. At the utility scale, PV power plants are now reaching the size in mega watts and growing further.

Recent years have seen rapid progress in the PV power plants. The global installed capacity of solar PV power plants in year 2000 was 1.5 GW which reached to 70 GW in year 2011 [2]. At the end of year 2017, the global installation of solar photovoltaic (PV) power plants had reached up to 402.5 GW [3].

Increase in the PV plants has resulted in various technological advancements in the field. With more advanced systems, there come complications along. The internal power electronics of the PV components have become complex. Also larger the size of the PV plant, the probability of occurrence of an error also increases. Errors can be minor which may be ignored as they may not be affecting the energy yield of the power plant. However, faults or errors can be severe which, if not dealt with, may result in lower yield. The lower yield not only reduces the financial return on investments but also hurdles in achieving the goals of green and clean energy.

1.3 Motivation

It is considered that the solar PV plants require very minimal maintenance, however the case can be different if a fault in the PV array, spanning to an area in some square kilometers, has appeared. At a small scale installation, it may be possible to detect and locate the fault easily by physically checking the voltage and current parameters, further if there are batteries installed for charge storage then battery life is also a factor that requires frequent check up. Large scale installations of PV power plants are difficult to have a battery backup as huge power banks are required, further their maintenance and life expectancy varies, grid-connected model is generally taken as a normal practice for power plants beyond 10-15 kW. Grid Connected PV plants are usually considered maintenance free as there are no batteries, no moving parts as in turbines in thermal generation systems and with only requirement of solar panels kept clean. Even though the grid-connected solar PV power plants are simple and usually remain error free, still it is important to have a monitoring system that can highlight any alarms that may arise in case of a fault occurrence.

This study has been conducted with the motivation to develop and implement a simple fault detection system for large scale solar PV plants. It has been kept in mind that the proposed system should be robust enough so the PV plants which implement this fault detection system may have better errors indication mechanism and reduced shutdown times. This will increase the total power plant yield and eventually increase in production of green energy and reduction of carbon emissions for our better tomorrow.

1.4 Overview of Solar Power Plants

A brief overview of solar power plants is presented in this chapter in order to discuss the major components and their significance in a power plant. The main focus is the photovoltaic power plants. Further the components of solar PV plants and topologies of PV plants are described here.

1.4.1 Types of Solar Power Plants

Solar power plants are generally categorized under two broad categories, solar photovoltaic power plants and concentrated solar thermal power plants. The difference is based on the fact that the sunlight carries two types of energies that can be utilized in energy production. One of these is the photon energy carried by the photons in the light, second is the heat energy that comes along.

1.4.1.1 Concentrated Solar Thermal Power Plants

The concentrated solar thermal power plants utilize the heat energy of the sunlight. The sunlight is converged on a single point, usually on top of a high tower. At top of that tower, water tank is constructed. The heat causes the vessel to heat up to a level that the water starts reaching its boiling point. The steam produced from the water heating is used to run the turbines and electricity is produced by the alternator coupled with the turbine. Also the steam is used for heating purposes.

Concentrated solar thermal plants are usually installed in GW capacity. These power plants have a problem that the ecosystem gets affected as the flying birds get struck with concentrated rays of light from heliostats die immediately because of excessive heat and this causes damage to the surrounding flora as well.

1.4.1.2 Solar Photovoltaic Power Plants

It is now commonly known that the word 'photo' means light and 'voltaic' means electricity so the word photovoltaic is used for electricity produced from the sunlight. In case of PV plants, the heat energy is not the driver of energy generation but the photons. The photons fall on to the surface of solar cells and penetrate in to the atomic level, where electrons are hit with these photons and holes are created. The phenomenon of the separation of charge carriers causes flow of current, in other words production of electricity. Solar cells are combined in to a series-connected set which is encapsulated in a vacuumed enclosure, called a PV module or PV panel. Now grown and a mature technology, the PV modules are normally created with wafers based crystalline silicon cells or thin films.

1.4.2 Major Components of PV Plants

1.4.2.1 Solar PV Modules

The solar PV modules produce DC electricity which is then converted to AC or consumed directly as DC as per requirement. The PV modules are of many types today, based on the composition, sunlight to electricity conversion efficiency and power output rating, etc. The most common and commercially available technologies of PV modules are monocrystalline silicon, polycrystalline silicon and thin film based PV modules. These types have their own positives and negatives and naturally the selection depends on the application. The PV modules are connected in combinations of series and parallel connections based on the voltage and current requirements. Generally the complete set of PV modules installed in a PV plant are referred as 'PV array'.

Crystalline Silicon PV Modules

The monocrystalline PV modules are made from silicon wafers formed with a single crystal. The unbroken crystal makes the appearance uniform and continuous structure with no grain boundaries [4].

The polycrystalline PV modules are made with multiple small crystals called crystallites. The surface of a polycrystalline cell has visible grain boundaries that give the polycrystalline PV modules their different appearance [5].

Thin-Film PV Modules

The thin-film PV modules are made by depositing thin films of semiconductor material on glass. There are several further types of thin-film PV modules, including cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si).

The PV modules vary in efficiency and performance under different conditions. Monocrystalline PV modules are considered better than other types in terms of performance. Thin-film PV modules are cheaper but larger in size when compared with other technology PV modules at same power rating [6]. Monocrystalline, polycrystalline and thin-film PV modules are shown in Figure 1.1.

Performance of PV Modules

The performance of PV modules depends on two very important factors, the sunlight intensity/irradiance and the module temperature. The irradiance is the measure of power that can be produced by the sunlight inclining on unit surface area. Irradiance is measured in Watts per square meter.

The PV module temperature is important because as the temperature rises the collisions at the atomic level increase which results in resisting the flow of charge.

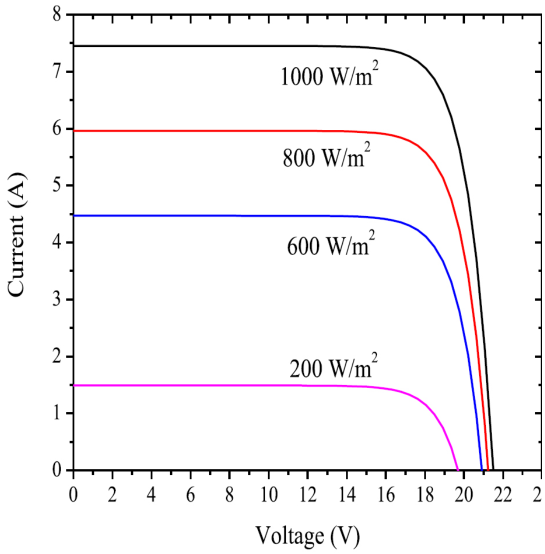
Higher the irradiance, higher is the PV module output, whereas, if the temperature increases beyond 25°C then the output starts degrading. The PV modules are normally rated in Watts. This rating is based on the output of PV module that it could give under certain values of irradiance and module temperature. These values are referred as 'standard test conditions' (STC) and are used for quality testing in laboratories as well. 1000 W/m^2 of irradiance and 25°C are the STC and a PV module rated at 270 Watts capacity would yield a power of 270 Watts under these conditions.

(a) Monocrystalline (b) Polycrstalline (c) Thin-Film

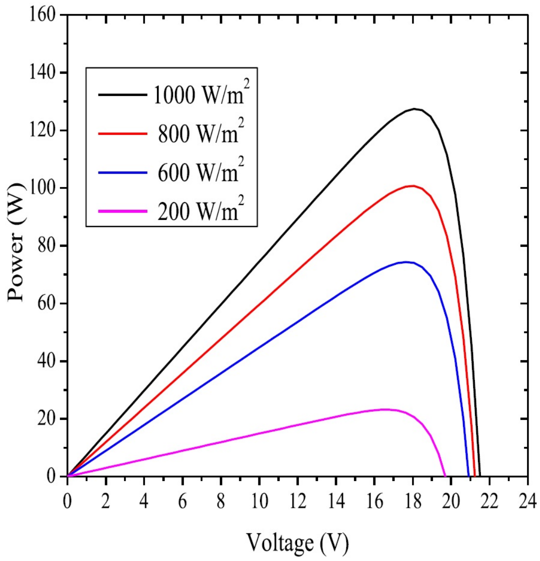
Figure 1.1: Types of PV Modules

Aging is also a factor which reduces the PV module outputs. Generally the PV modules are considered to live up to 25 years, however, these still are able to produce power but their efficiency is reduced so much that they are considered for replacement with new ones. PV modules drop to about 2-2.5% of their nameplate capacity after 1 year of operation and then a linear decrease is seen through rest of 24 years.

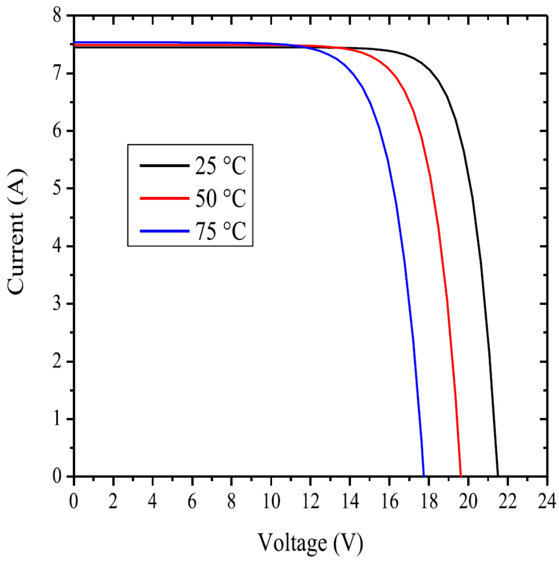
The effects of irradiance, module temperature and aging are provided in the datasheet of PV modules by the manufacturers. This helps in better prediction of output of PV power plants upon different weather conditions and gradual effect of aging can also be incorporated in the PV output forecasting. The output characteristics of PV modules are represented with help of current to voltage (IV) and power to voltage (PV) curves. Also the tolerance against the harsh environment conditions severe wind storms, hail storms and pressure, etc are also mentioned in the datasheet of PV modules in order to have knowledge and understanding for the PV plants designers to select proper type of PV module for their specific conditions. The IV and PV characteristics of a PV module under varying irradiance are shown in Figure 1.2 (a) and (b) respectively. The effect of temperature at a constant irradiance on the IV and PV characteristics of a PV module is presented in the Figure 1.2 (c) and (d). The aging effect of PV module is shown in Figure 1.2 (e).



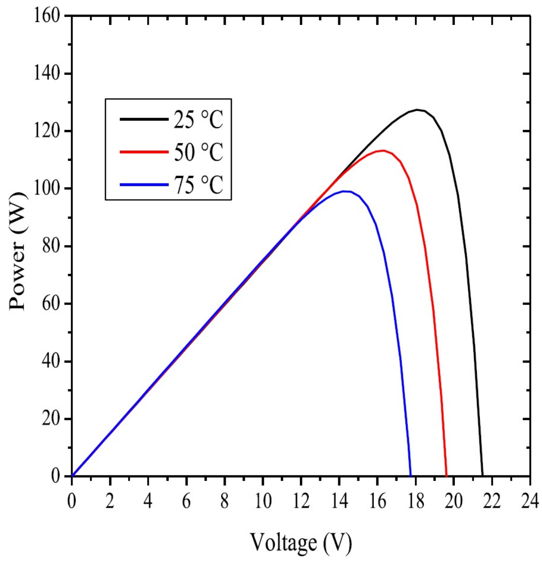
(a) IV Curve under Varying Irradiance [7]



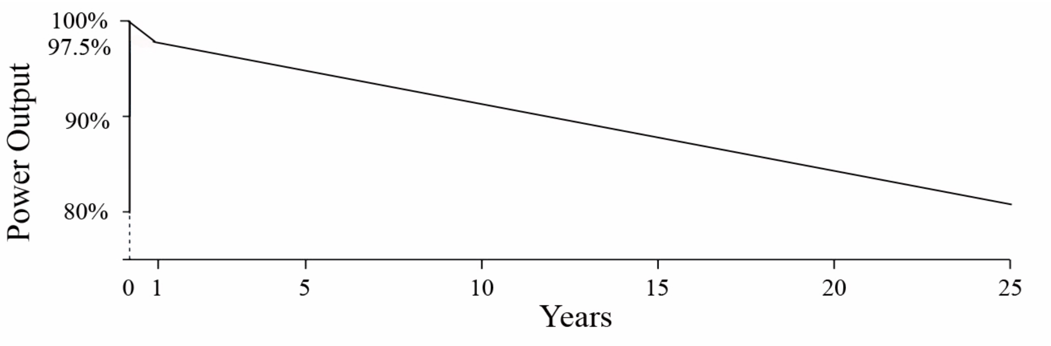
(b) PV Curve under Varying Irradiance [7]



(c) IV Curve under Varying PV Module Temperature [7]



(d) PV Curve under Varying PV Module Temperature [7]



(e) Gradual Degradation of PV Module due to Aging

FIGURE 1.2: Varying Performance of PV Modules under different conditions and time [8]

1.4.2.2 Inverters

Inverter is the power electronics device that converts the DC electricity coming from the PV modules in to AC electricity for use. Inverters are built as per the mode the operation. The mode of operation can either be grid-connected, standalone or bi-modal. These modes of operation are discussed in detail in the section 1.4.3.

Inverters can have single or multiple input ports for DC power input and the PV array is installed in accordance with the specification of inverters in order to conform with the input voltage and current threshold limitations. The inverters play critical role in a grid-connected PV plant because there is no DC load and if inverter is not functioning then the PV plant stops working completely.

1.4.2.3 Batteries and Charge Controllers

Batteries are used in the PV power plants to store energy which could be used later. The batteries provide a backup to PV plant so when sunlight is not available then the charge stored in the batteries may power up the connected load.

The charge controllers are the components that connect the batteries with PV modules. Energy passes through the charge controller in order to be stored in the batteries. The charge controllers, as the name suggests, control the charge and prevent batteries from over charging. Charge controllers may also provide other features like battery health and temperature monitoring, etc.

1.4.2.4 System and Environment Monitoring Units

The system monitoring units provide the energy yield reports of the power plants. The power plant operator may be able to observe any abnormalities with the help of system monitoring units.

The environment monitoring systems provide data of the environment conditions especially the sunlight intensity/irradiance and the PV module temperature. The environment conditions are usually helpful in order to understand the performance of PV plant under different weather conditions.

1.4.2.5 Maximum Power Point Tracking

Maximum power point tracking, or MPPT, is normally a built-in functionality of the inverter. The function of MPPT is to track the maximum power point of the PV array in real-time. The MPPT unit continuously monitors the power output of PV array and performs certain actions to obtain maximum yield under prevailing weather conditions.

1.4.3 Topologies of Solar PV Plants

There are three common topologies are used while installing a PV power plant. Inverters for different topology are different. These topologies are explained as under.

1.4.3.1 Standalone PV Plants

The standalone PV plants are those which are isolated from the grid supply. There is no external power connection and only the PV modules are power producing/-supplying source. Further the energy produced from the PV array is stored in the batteries which may be used for later purpose [9]. Standalone PV plants are also called ‘off-grid’ or ‘grid-isolated’ PV plants, shown in Figure 1.3.

1.4.3.2 Bi-Modal PV Plants

Bi-modal PV plant is a combination of standalone and the grid-connected PV system. The PV plant is connected with the grid and can provide its surplus energy to the grid and at the same time it can store energy to provide for later

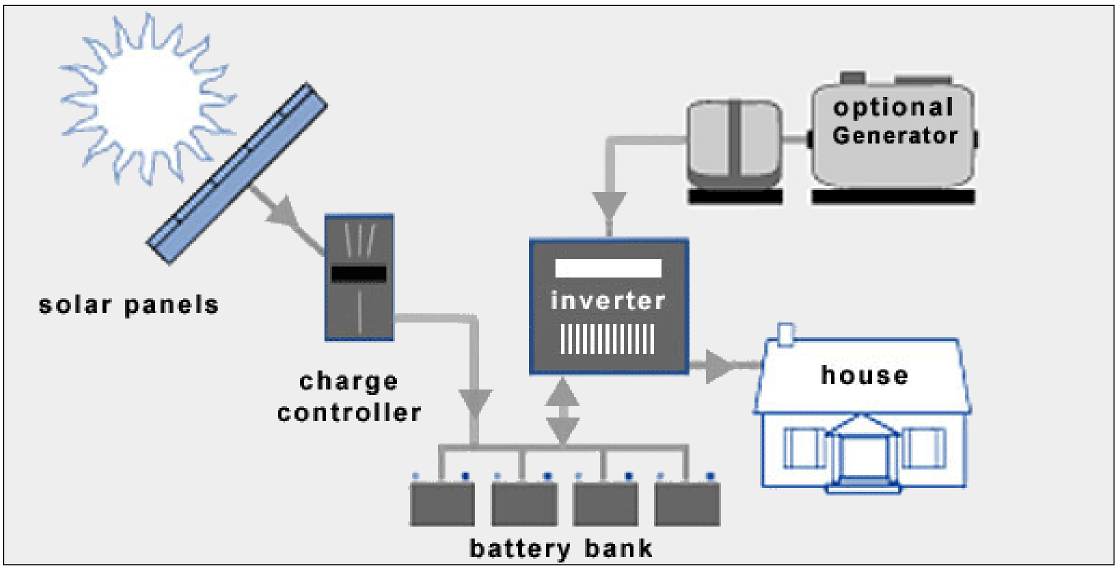


FIGURE 1.3: Design of Standalone PV Power Plant [10]

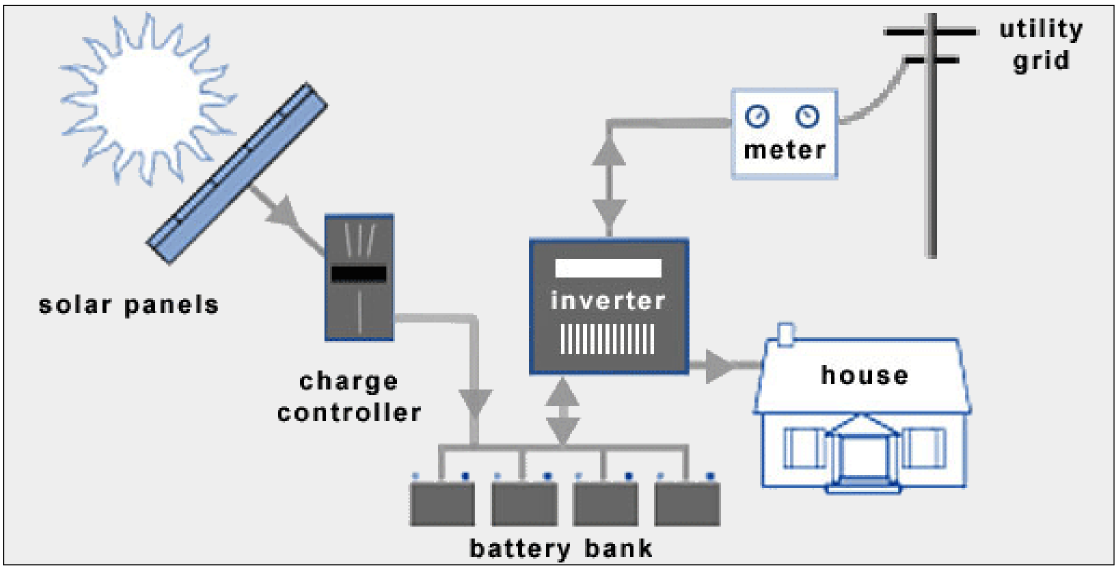


FIGURE 1.4: Design of Bi-Modal PV Power Plant [10]

usage [9]. Bi-modal PV plants are also called 'hybrid' PV plants. Bi-modal PV plant design is shown in Figure 1.4.

1.4.3.3 Grid-Connected PV Plants

The grid-connected PV plants are those which have their AC output coupled with the grid power supply. The inverters which are designed to operate in this mode sense the voltage and frequency from the grid and give their output accordingly

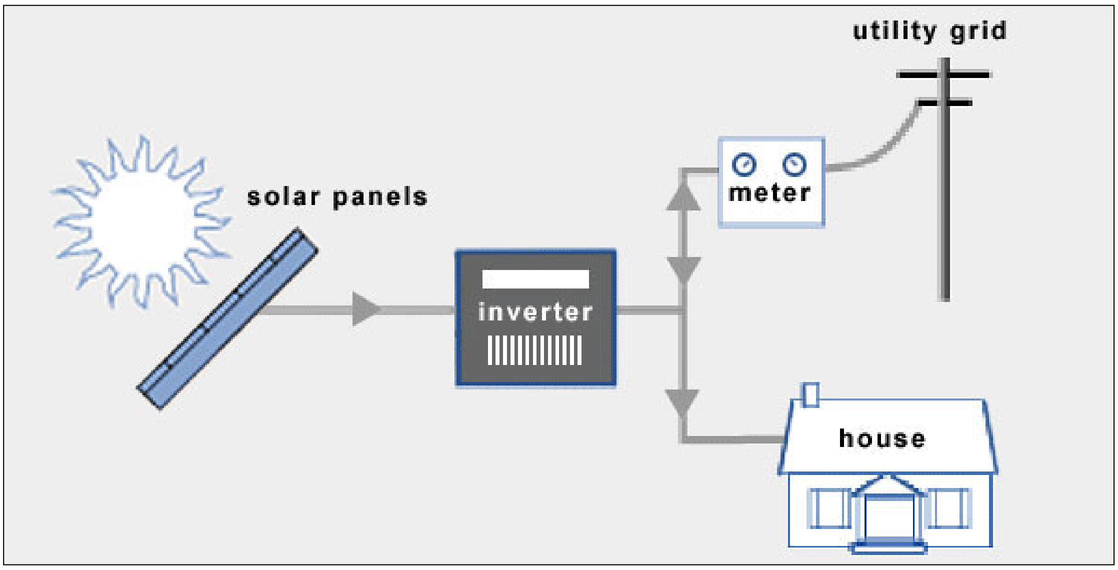


FIGURE 1.5: Design of Grid-Connected PV Power Plant [10]

[11]. The grid-connected PV plants do not have any battery backup for charge storage, all the energy produced is consumed on spot or fed in to the grid. Grid-connected PV plants are also called 'on-grid', 'grid-tied' or 'grid-integrated' PV plants. Basic design of grid-connected PV plant is shown in Figure 1.5.

Grid-connected PV plants are the most obvious and preferred choice when designing a large scale PV power plant. The simple design, easy installation and lesser limitations make the financial feasibility of grid-connected PV systems far better than rest of topologies. The feed-in energy to grid concept helps industries to deploy grid-connected PV systems and supply their surplus energy to grid and consume from grid when their requirement exceeds. Further, the net-metering concept helps achieve better pay-back times.

1.5 Objective

The objective of this thesis is to develop a simple and practically viable approach to a fault detection mechanism which is able to trace a fault and diagnose the fault type. The aim is to develop and test an algorithm that would be applicable to variety of solar power plants, especially large scale power plants ranging from 100 kW up to a capacity in mega watts. The size of power plants should not affect the algorithm's operation and it should be simple enough to be deployed without any special requirements.

The key objectives of this work are:

- To understand the operation of a grid-connected PV power plant and trace out the most commonly occurring faults in the DC side of power plant.
- To model and simulate a grid-connected solar PV plant based on a physically installed PV power plant.
- To analyze the performance of the modeled grid-connected PV plant under different weather conditions with varying irradiance and temperature.
- To develop a fault detection algorithm that can detect and identify faults in a large scale grid-tied solar PV power plant.
- To test the developed fault detection system under different scenarios to observe the performance and reliability of developed system.

1.6 Thesis Outline

The rest of thesis is organized in following chapters:

Chapter 2

The chapter 2 of this thesis presents literature review and discusses the work conducted on the fault detection algorithm in grid-tied PV power plants. The chapter also identifies the gap and formulates the problem statement. Later, proposed methodology for the research work is presented to explain about the software tools, modeling of PV plant, conclusion and future work presented in this study.

Chapter 3

This chapter discusses the proposed fault detection system, starting with the description of the power plant which is taken as reference for development of this algorithm and the application of algorithm is tested on. The MATLAB ® and Simulink ® model for the said power plant is described in detail.

The fault detection algorithm and flowchart of fault identification is presented in this chapter.

Chapter 4

The algorithm is analyzed under different scenarios and results are evaluated in this chapter. The algorithm outcomes are explained. Limitations of this fault detection algorithm are mentioned and complete thesis is summarized in the end.

Chapter 5

Chapter 5 gives the conclusions drawn from the study work. Later the recommended future work is outlined at the end.

Chapter 2

Literature Review

2.1 Literature Review

In the recent years several studies have been conducted for detection of faults in grid-tied photovoltaic systems. There are some techniques which use satellite imaging approach to estimate the solar irradiance and DC power of PV array to detect the faults. The technique in Ref. [12] uses GISTEL (Solar Radiation by Teledetection) in combination with fuzzy logic control system to detect the occurrence of a fault, and then currents and voltages ratios are used to identify the nature of a fault.

The authors in Ref. [13] discussed two ways to detect fault in a PV string, based on earth capacitance measurement and time-domain reflectometery. The earth capacitance measurement method helps detection of fault position in the PV string, whereas the time-domain reflectometery is used for measurement of electrical characteristics to detect the breakdown point. The authors also mention that the first method is useful for examination of PV power plants in case of disasters and the second technique is to be used for regular inspection of PV power plants to detect the faults.

The authors in Ref. [14] used approach of generating several diagnostic signals to highlight occurrence of a fault and then DC to AC power ratios determine the nature of the fault. This study discussed the fault types of faulty PV modules in a string, complete faulty PV string, fault in the inverter and partial shading, MPPT error and ageing of PV modules as a grouped fault. The authors mentioned that this technique is also able to detect a false alarm from the diagnostics system. This study was validated by the authors on a rooftop PV plant of 20 kW capacity installed in Italy. These authors in Ref. [15] presented another faults detection technique for PV power plants using artificial neural networks (ANN). This technique detects a fault in the PV system using set of conditions such as irradiance and PV module temperature and attributes such as PV string's voltage, current and number of peak currents appearing in the IV curve of the PV string. This study was validated by the authors on a PV plant installed in Renewable Energy Laboratory (REL) of University of Jijel, Algeria by implementing the technique on field gate programmable array (FPGA).

The fault detection approach presented in Ref. [16] is based on comparison of simulated and measured results of AC power of the PV plant. This paper also uses performance ratio which is the ratio of energy yield and installed capacity in relation with the available irradiance. This study has been validated on a 120 kW PV plant installed in Toronto Canada, however, the study does not categorize the faults. The technique only highlights that a fault has occurred but is not designed to identify the nature of fault.

Another fault detection procedure is presented which uses current and voltage indicator and defines thresholds for these indicators to detect faults of fault in a PV string or a bypassed PV module [17]. These authors further extend their work in Ref. [18] and validate their findings using two PV power plants with 9 kW and 900 Watts size installed in Algeria and Spain respectively.

Authors in Ref. [19] presented fault detection system using ANN for detection of line-to-line faults with small voltage difference, line-to-line faults with large voltage difference, open circuit and degradation fault. The study was performed by simulating grid-tied PV plant in MATLAB based on acquired data of irradiance and temperature of PV modules.

Another technique of fault detection using wavelet packets is presented in Ref. [20]. The study uses discrete wavelet transform as continuous wavelet transform is time consuming. The authors state that wavelets technique is used because it is a suitable approach to analyze the transient characteristics of different faults. This study discusses and implements the detection algorithm for line to line fault with one PV module and with more than one PV modules mismatch and partial shading on the PV array.

The technique presented in Ref. [21] compares ideal and faulty PV plant for detection of faulty PV modules categorized as interconnection resistance fault and partial shading fault. The study gives thresholds values in power deviations for normal and faulty conditions.

One of the most extensively conducted works on study of the fault detection algorithms for grid-tied PV power plants has been presented by Mahmoud Dhimish and Violeta Holmes. The Ref. [22] detects defective bypass diode in the PV module. In Refs. [23], [24], [25] and [26], the authors use statistical operation of T-Test to detect a fault. Power ratio and voltage ratio between theoretical/simulated PV plant data and measured PV plant data are used to identify the fault type. The simulation PV plant data is achieved using modeling in LabVIEW software. The study in Ref. [26] is conducted on a 1.98 kW grid-tied PV power plant installed in University of Huddersfield, UK.

The above discussed studies have been conducted mostly on small sized PV plants ranging up to 20 kW. All of the techniques define certain kind of indicators which are used to detect a fault condition and then the ranges defined for these indicators distinguish between different kind of faults. Some of the techniques have used artificial neural networks, some have used fuzzy logic while some have used simple methods such as power ratios and voltage ratios between AC and DC powers of PV plants.

The next section gives analysis of gap in above discussed literature. A problem statement is formulated to conduct a study on real-time fault detection system in large-scale PV power plants.

2.2 Gap Analysis and Problem Statement

As discussed in the section 2.1, it is observed in most of the available work that the fault detection algorithms are implemented and tested based on the PV power plants which cannot be categorized under large scale PV power plants because these power plants are around the size of a few kW. In such PV plants, the string sizes are small and number of PV strings is also limited to a small number. Ref. [16] performed the study based on a 120 kW grid-tied PV system; however, it does not differentiate what kind of fault has occurred but only detects normal and faulty conditions.

The Refs. [23], [24], [25] and [26] present an extensive work but their approach does not appear to be applicable to all systems as their presented formulae for power ratio and voltage ratio cannot be generalized. The power ratio used in these studies are for complete DC power from the PV plant however as the size of PV plants increases then the faults such as PV modules failure and partial shading on a single PV module does not contribute their significant effect, so the power ratio may not be very clearly categorized for several faults. The voltage ratio may not be able to work well in situations where a complete string gets disconnected then voltage ratio will not show any deviation and fault will not be detected.

Considering the limitation of techniques being tested only on small sized power plants, it is felt that a fault detection algorithm for grid-connected PV systems is needed that is able to be used in large scale power plants and the algorithm is able to explicitly identify different faults.

2.3 Research Methodology

2.3.1 Software Tool and Modeling of PV Plant

The research is conducted based on modeling and simulation of solar PV plant and acquiring results to present the conclusion. MATLAB® is used for modeling of PV power plant with help of its very powerful tool, Simulink®. The modeling results are collected and a fault detection system is developed in the MATLAB script code. This fault detection system takes inputs from the Simulink model and produce results on a GUI. The GUI is created in GUIDE tool of MATLAB.

The MATLAB® R2018a is considered for the modeling and simulation purpose because of its well equipped library in Simulink. The Simscape Power Systems provide the PV array component which can be configured as required according to the size of PV plant. The measurement instruments for voltage and current are quite handy in Simulink to get the values at any location.

An operational grid-integrated PV power plant is taken as reference to model the PV plant in MATLAB. The modeled PV plant is developed such that the PV output resembles to that of reference PV plant. The fault detection system is implemented and simulated based on weather conditions of different days so the results are sufficient enough to draw valid conclusions.

2.3.2 Conclusions and Future Work

The conclusions of the study are presented based on the results as achieved from the simulations under various test conditions. The conclusions drawn in the thesis are presented such that it can be easily assessed if the proposed system is applicable to someone's requirements or not. Finally, the advantages and limitations of the proposed fault detection system are also highlighted to clearly mention its application.

At the end of the study, future work is recommended to further test the proposed fault detection system. Different conditions and types of faults which cannot be covered in this study due to any reason are also highlighted which can be later incorporated in this detection system to trace and identify more faults.

Chapter 3

Modeling of PV Power Plant and Fault Detection System

This chapter presents the modeling and simulation of PV power plant based on an actually operational solar power plant which acts as our reference for testing of the proposed fault detection algorithm. Later the fault detection system is proposed in this chapter with details on the basic idea of fault detection, developed mathematical operations for the detection system and algorithm flowchart.

3.1 Reference Solar PV Power Plant

The 125 kW Solar Power Plant installed at the Wah Nobel Group of Companies, Wah Cantt has been used as reference solar power plant for this study. The said power plant was installed in the year 2014 and is integrated with the local grid network. The energy incoming from grid and outgoing from the solar plant is measured with a bi-directional energy meter that is used for billing purpose by the distribution company. The subject power plant is taken as reference as its installed capacity is higher than 100 kW satisfying our definition of large scale PV plants.

The details of installed equipment are given in the following subsections.

3.1.1 125 kW Solar PV Plant

3.1.1.1 PV Modules

The PV modules used in the power plant are Yingli Panda 60 Cell 270 Watt size. Panda is the monocrystalline series of Chinese PV manufacturer Yingli. A total of 462 number of PV modules are installed in this plant.

The PV modules are connected in series forming up a string. One string has 22 number of PV modules and three strings are connected in parallel in a combiner box. There are total of 21 strings and 7 combiner boxes. Each combiner box has equal three number of PV strings. The seven DC positive and negative pairs of connections terminate at the DC busbar of inverter as parallel connections. The connections of PV strings and inverter are illustrated in the single line diagram in section 3.1.1.5.

The specifications under the Standard Test Conditions (STC) of PV module are given in Table 3.1.

3.1.1.2 Inverter

Inverter used in the solar PV plant is Sungrow SG125KTL. The grid-tied inverter has DC input capacity of 141 kW and it yields a maximum of 125 kW of 3 phase AC power with 400 VAC and 50 Hz output. The inverter specifications are given in Table 3.2.

3.1.1.3 Environment Monitoring Unit

The Sungrow SolarInfo EM (SSYW-01) provides features of pyranometer and temperature sensor. This is used for acquiring the real-time environment conditions, i.e., solar irradiance and PV module temperature.

The environment unit also provides ambient temperature, wind speed and direction.

TABLE 3.1: Specifications of PV Module

Manufacturer	Yingli, China
Model	YL270C-30b
Module Type	Monocrystalline
Power Output at STC	270 W
Module Efficiency	16.5%
Voltage at Pmax (V_{mpp})	30.61V
Current at Pmax (I_{mpp})	8.82 V
Open-circuit Voltage (V_{oc})	38.48 V
Short-circuit Circuit (V_{sc})	9.45 V

TABLE 3.2: Specifications of Inverter

Manufacturer	Sungrow, China
Model	SG125K
Maximum DC Input Power	141 kW
Maximum DC Voltage	1000
C Rated Power	125 kW
Maximum AC Apparent Power	137.5 kVA
Grid Voltage	400 V
Grid Frequency	50/60 Hz
Maximum Output Current	275 A

3.1.1.4 Power Plant Monitoring System

The existing power plant monitoring system is Sungrow SolarInfo Logger. The device receives the power output data from the connected inverter. The combiner boxes which connect the PV strings have separate voltmeters and current transformers to measure the voltages and currents of all strings. The output of these measurement devices is connected with the communication module of inverter. Inverter sends the information of combiner boxes and its output to the SolarInfo Logger. SolarInfo Logger is connected to a work station for real-time display of DC power output and AC energy. SolarInfo Logger keeps log of daily data and keeps record of several parameters. If there are any abrupt changes in the average values of the power then the system raises an alarm of deviation from the average outputs. This helps the power plant operator to know that something has gone wrong; however, the type of fault is not indicated.

3.1.1.5 Single Line Diagram

The single line diagram of the reference PV power plant is shown in the Figure 3.1. It is seen that 22 number of series-connected PV modules form up a string. 3 number of strings are connected in parallel at a combiner box (CB). The 7 combiner boxes output the DC power and the inverter DC busbar combines the outputs of all combiner boxes.

The inverter converts the DC power to AC power as per the voltage and frequency of the grid. The main breaker acts as the isolation circuit breaker between the inverter output and the grid supply. The transformer is a 500 kVA rated 230/400 VAC 3 phase transformer which steps up the inverter output to 11 kV for power feed-in to the grid.

3.1.2 Faults in DC Side of PV Power Plant

DC side faults in the grid-tied PV plant are important because these faults do not always cause a system shutdown and no indication may be there for the plant operator to know if the output is normal or it has any fault. AC side faults are critical in terms of safety but normally the inverters and isolation components have protection from AC side faults and the system shuts down to prevent any damage to equipment, also power plant shutting down itself is a good enough indication to let the operator know of an AC side failure. AC side faults like grid voltage fluctuations, frequency fluctuations and anti-islanding protection usually cause inverter shut down, hence the system remains safe and the operator is well-aware of the fault. The types of DC side fault that are addressed in this study are discussed as under:

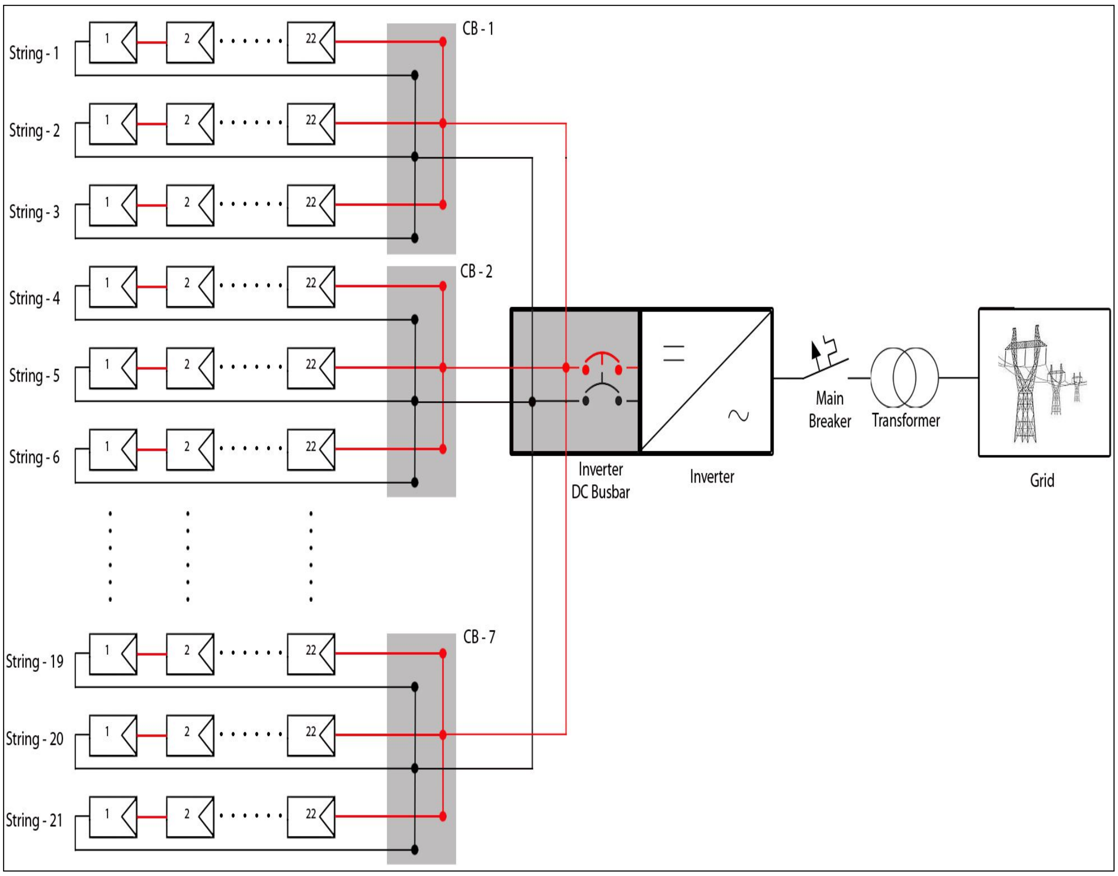


FIGURE 3.1: Single Line Diagram of Reference PV Power Plant

3.1.2.1 Faulty PV Modules (F1)

In this study, a faulty PV module refers to a short-circuited PV module, or PV module removed from the string. This means that whenever a PV module has short-circuited, only the number of PV modules is reduced in the respective string, rest of the modules in string keep on producing DC electricity. Let us consider a case of a large scale PV plant where modules are in hundreds, then a single PV module failure is a negligible effect on the power output. As the series-connected PV modules contribute their voltage to the string and current remains same for any number of modules in that string, so if a single module is short-circuited the bypass diode will come into play passing the same amount of current and the MPPT module which is regulating the DC voltage will slightly increase its output voltage to remain at the MPP level. Therefore, a single module fault has not been considered significant in this study. It is observed that a measureable effect occurs on the PV string when at least 5 PV modules are gone off in the string.

In addition, if size of PV string is reduced to a certain level that the operational modules of the string are unable to compensate the voltage and meet the minimum required DC voltage by the inverter then the complete string stops working. In this situation the current of string will increase so much that the protection circuit breakers in combiner box will trip off and string will get disconnected.

The proposed algorithm considers and detects PV modules fault of 5 PV modules in a string. This fault is referred as 'Type 1 Fault' or 'F1' in this study.

3.1.2.2 Faulty PV String (F2 and F3)

A faulty PV string means the string that has been disconnected from the system, either due to cable breakage, tripping or any other malfunctioning. A single PV string failure or multiple PV string failure are considered as separate faults in this study to highlight that the algorithm is able to diagnose simultaneous failures occurring in the DC side.

A single string failure means a significant size of PV array not yielding any power. In case of our reference power plant, where a single PV module is 270 W in size and there are 22 number of PV modules in a string, ideally a 5,940 W or 5.94 kW of power has gone from the PV plant. Single PV String fault is referred as 'Type 2 Fault' or 'F2' and multiple strings fault is referred as 'Type 3 Fault' or 'F3' in the study.

3.1.2.3 MPPT Failure (F4)

MPPT unit is very important in the DC side of the PV plant. The MPPT unit regulates the DC voltage output from the PV array to optimize the performance of the PV plant. If the MPPT does not work then the DC voltage may not be operating at the optimum value and a significant drop in power generation will occur. The MPPT unit failure is an important fault that needs to be detected and highlighted as soon as possible and it is referred as 'Type 4 Fault' or 'F4' in this study.

3.1.2.4 Partial Shading and Soiling Loss (F5)

Partial shading on a PV module means that some portion of a module is under shading effect. The PV modules are manufactured such that certain number of cells is connected in series and a bypass diode is connected in parallel to these cells. If a set of cells has lower output current than the rest of cells then the bypass diode will pass the current bypassing or disconnecting the faulty cells. It is observed in a large sized PV power plant that partial shading on a single module or a part of module in a total of hundreds of PV modules will not put any effect on power output, because such small power deviations are not only insignificant but quite difficult to observe as well.

A faulty bypass diode has not been considered as a fault here. The bypass diode comes into action when there is partial shading on a single module.

Soiling loss is also critical when large scale PV plants are under focus. PV modules usually require cleaning or washing of modules surface with water to remove the dust deposited on it. The dust particles settled on the PV modules prevent sunlight's photon particles to reach to the solar cell and perform the sunlight-to-electricity conversion efficiently. Therefore, there may be soil and dust deposited on the surface of PV modules resulting in reduction in DC power output, which is called as soiling loss. The soiling loss has similar effect on PV output as that of partial shading.

The partial shading or soiling loss having similar impact on power are taken as one fault and are referred as 'Type 5 Fault' or 'F5' in this study.

3.2 Modeling of Solar PV Plant

MATLAB® R2018a is used for the modeling and simulation purpose in the Simulink® for this study. The solar power plant is modeled using the Simscape Power Systems components. The PV component available in the Simulink library is used to model the PV strings. DC – DC converters, VSC (inverter), Step-up Transformer and Grid are also modeled in the simulation.

The PV component receives input of irradiance and module temperature and gives an output of DC power and measurements which give the values of PV Voltage, PV Current, Diode Current, Irradiance and Temperature on the PV array. The DC power from the PV strings is combined by connecting in parallel and then the combined DC power is fed in to the inverter for conversion to AC power. The Inverter unit contains the DC – DC converter which is controlled with output from MPPT unit, Inverter Control unit to provide controlling function for switches to produce AC electricity.

3.2.1 Simulation Model

Two PV power plants are modeled in the simulation. The purpose of two PV plants modeling is better understood once the fault detection system is described in later section of this chapter. One of the PV power plants is named as the 'Actual PV Plant' which is taken as the PV plant which may have a fault in the system. The second is the 'Theoretical PV Plant' which remains same throughout the simulation. Both these power plants have their separate step-up transformers and grids modeled so no connection of either PV plant is established which may affect the results.

For simulation purpose, the irradiance and module temperature are obtained from the reference power plant's monitoring system with intervals of 15 minute for complete day. An excel spreadsheet is used to keep the irradiance and module temperature data for each day and "From Spreadsheet" component of Simulink imports the weather conditions to the simulation for input to the PV array. The 'Scopes' block is created which gives the output waveforms at different levels, such as PV array output voltage, current and power, the AC outputs from the inverter and grid power parameters and comparison graphs of Actual and Theoretical PV Plants DC outputs. The simulation model of this study is shown in Figure 3.2.

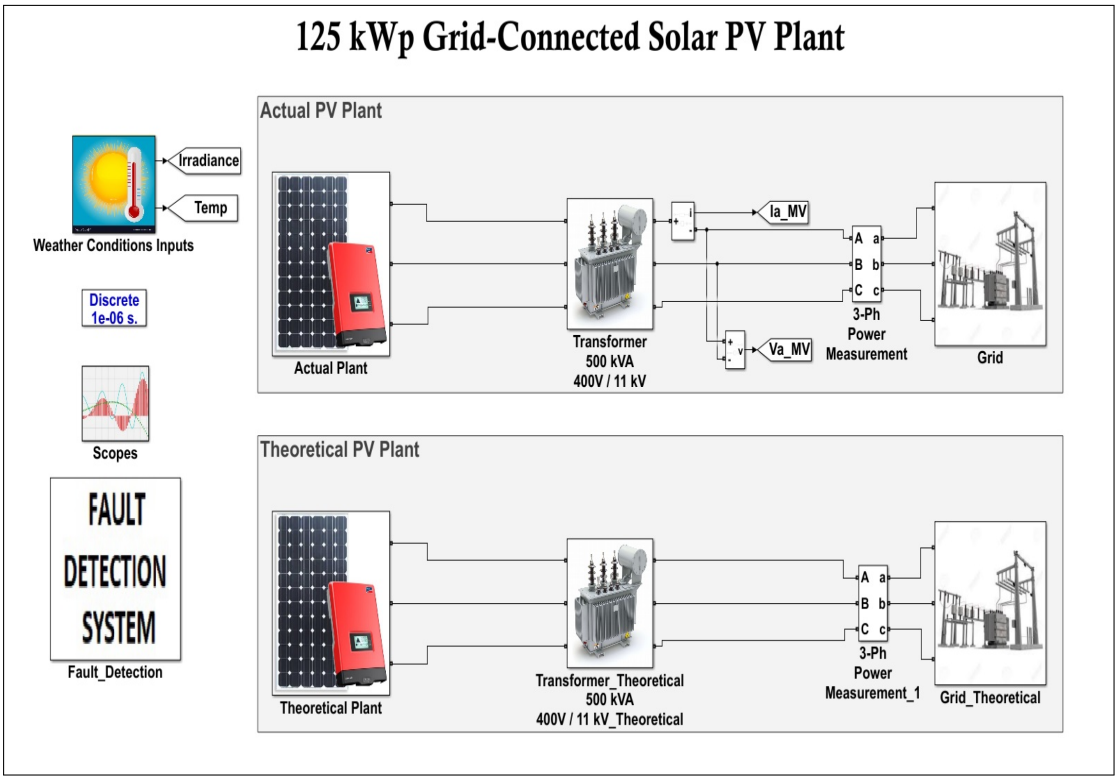


FIGURE 3.2: Simulation Model of 125 kW Grid-Integrated PV Power Plant

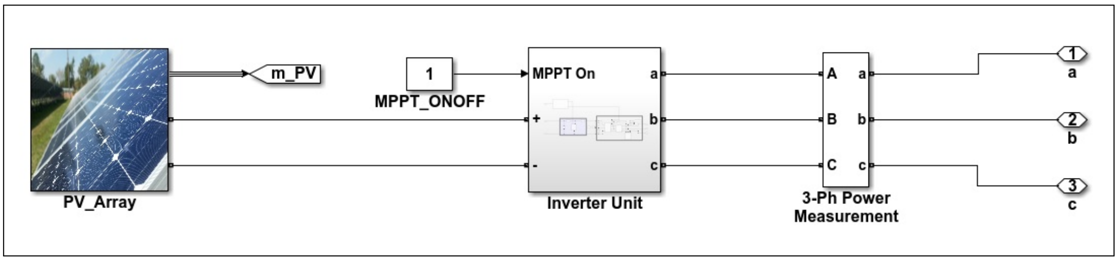


FIGURE 3.3: Model of PV Plant showing PV Array and Inverter of 'Actual PV Plant'

3.2.1.1 Actual PV Plant and PV Array

The 'Actual PV Plant' is the power plant corresponding to the physically installed solar power. It contains complete PV array including the 21 number of PV strings and Inverter unit, shown in Figure 3.3. PV array consists of PV components each representing one string. The PV strings are combined in parallel at 7 points and then finally merged in one DC connection which is terminated from the PV array. Since the reference power plant was installed in year 2014, a degradation factor of 4% is applied on the PV output to account for the aging effect of PV modules; therefore a gain of 0.96 is applied on the current of PV array. The factor 4%

degradation was calculated based on the degradation pattern as defined in the PV modules manufacturer datasheet. The PV array configuration is shown in Figure 3.4.

Inside each PV sub-array, there are 3 PV strings, which are modeled using the PV component of Simscape Power Systems. There are a range of solar PV modules from different manufacturers available in the Simulink PV component library. The module used in our reference PV plant Yingli YL270C-30b is available in the library and hence used for simulation. This component of Simulink is designed such that it is able to yield output as close to the real-life PV module as per the values of irradiance and module temperature.

The PV sub-arrays have been designed so that the voltage and current of all strings are measured for the use of simulation. One PV sub-array is shown in Figure 3.5 and the parameters of PV component are shown in Figure 3.6. In order to create a realistic approach in the PV system to incorporate the fact that all PV modules do not yield a uniform and identical power output and there is always some variation in output of 1 PV module from the other, random numbers are generated and multiplied with the output of all PV String current values. This helped in obtaining a varying yield of all the strings within a certain limit to simulate the factor of non-linearity.

3.2.1.2 Inverter Unit

The Inverter Unit consists of a DC-DC boost converter and a voltage-source converter (VSC). The DC-DC boost converter is used to step-up the DC voltage from the PV array. The step-up voltage is input in to the VSC which inverts the DC voltage to AC voltage. The VSC is based on the three phase bridge inverter. Such inverters are called voltage-source inverters.

The DC-DC boost converter is essential to maintain a value of DC voltage. Figure 3.7 shows the circuit of the boost converter. Boost converter works on the principle of inductor's property to resist a sudden change of current. As shown in the Figure

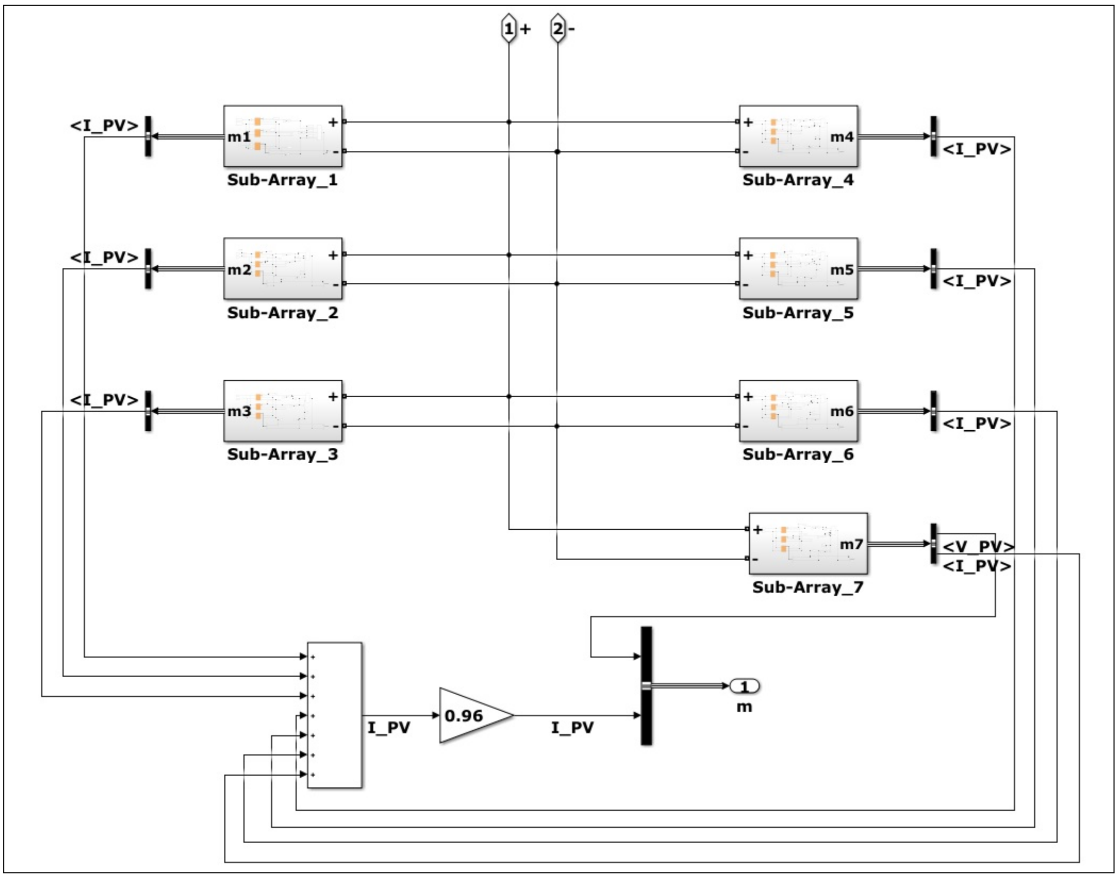


FIGURE 3.4: Inside of PV Array Block: Configuration of 7 PV Sub-Arrays

3.7, an IGBT switch is used to trigger the On and Off states. When the switch is On, the current passes through the diode and energy is stored in the inverter. This creates a magnetic field. When the switch is turned Off, the magnetic field decays causing flow of current in reverse direction. This results in increase in output voltage than the input DC voltage. The switching signal to the switch is provided by the MPPT module to optimize the voltage.

The MPPT technique used in the modeling is Incremental Conductance which is quite common and efficient technique. This technique is used because it gives the output power very similar to the reference power plant. The boosted DC voltage is given in to the VSC circuit where the 3-level IGBT-switched bridge outputs an alternating three phase voltage supply. The 3-level bridge takes switching signals from the inverter control to output voltage matching with the grid power supply.

The inverter unit output of 400V is given in to the step-up transformer and an 11 kV AC is then fed in to the grid network. The three-phase bridge rectifier is

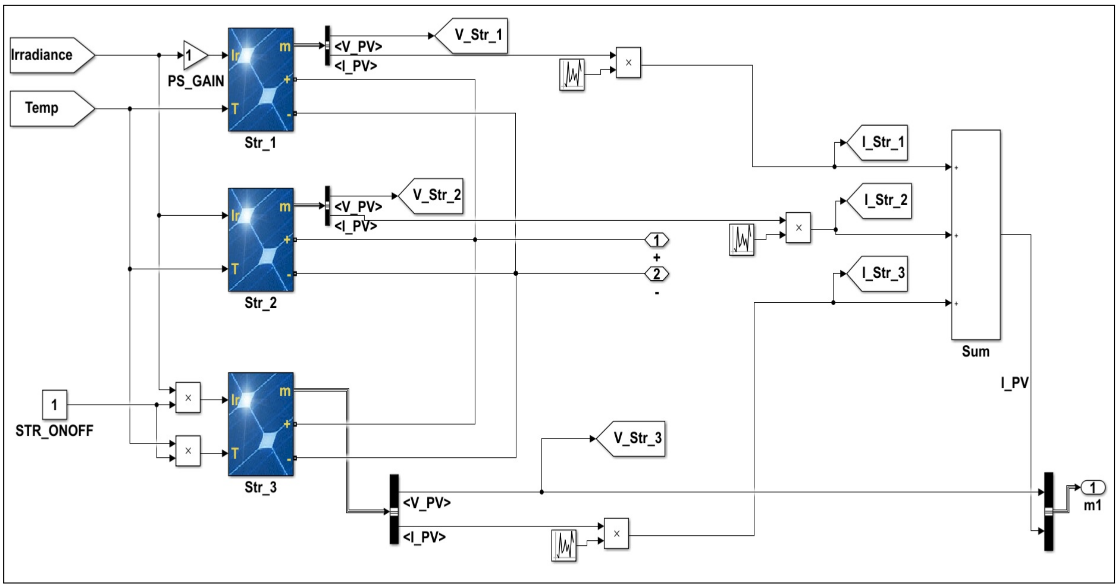


FIGURE 3.5: Inside of PV Sub-Array: Three PV Strings Connected in Parallel

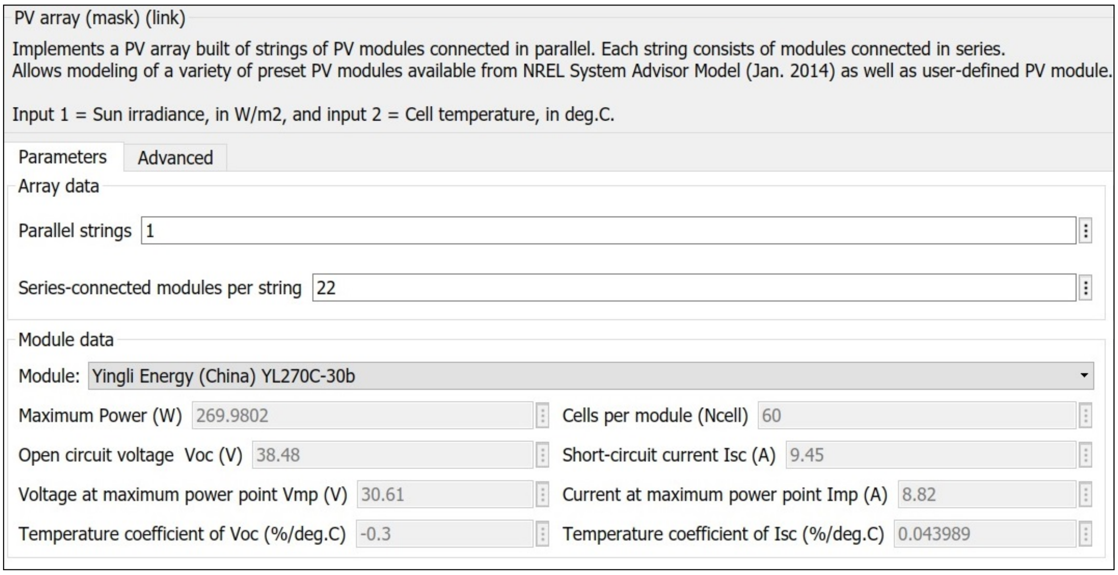


FIGURE 3.6: Parameters Setting of PV Component for One String with Yingli YL270C-30b PV Modules

based on the design as explained by M. H. Rashid [27] and the circuit diagram of this three-phase bridge inverter is shown in the Figure 3.8.

3.2.1.3 GUI and Fault Inducing Mechanism for Simulation

A GUI is designed in the MATLAB GUIDE that provides the front end interface, shown in Figure 3.9. There are two portions of GUI, one is 'Real-time Status

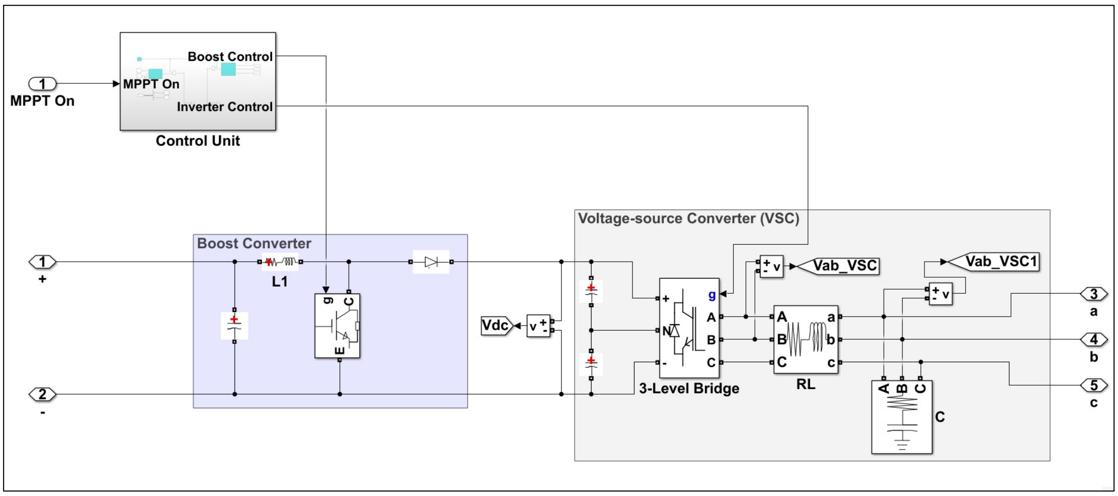


FIGURE 3.7: Model of the Inverter including Boost Converter, VSC and Control Unit to Generate Switching Signals for DC-DC Converter and VSC

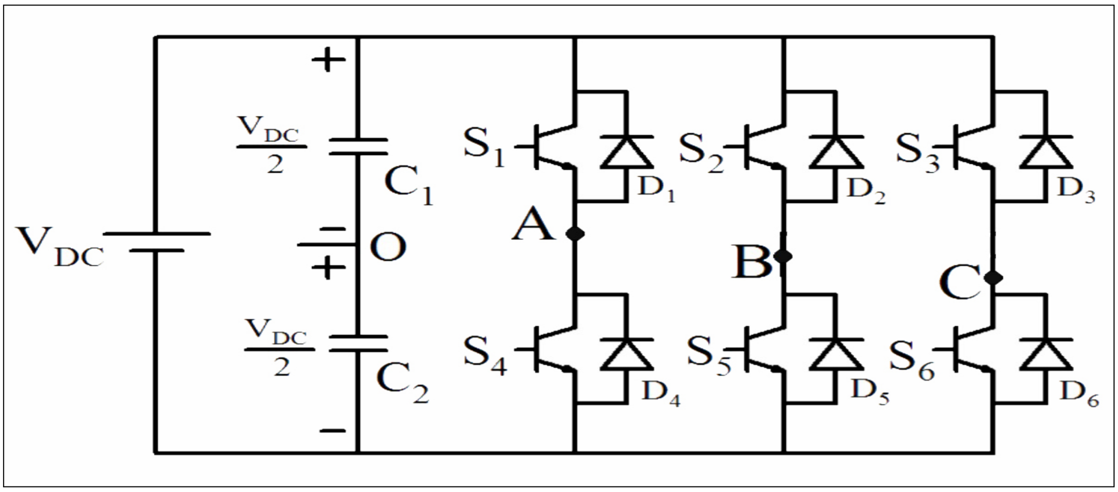


FIGURE 3.8: Three-phase Bridge Inverter Circuit Diagram [28]

Monitor' and other is 'Fault Setting Panel'. The GUI provides option to select the environment conditions based on several dates. Further, to test the algorithm, the faults can be induced in the Actual Plant at any time. When the Simulink model is running, the Fault Detection System periodically receives voltage and current of all strings, the algorithm is processed and the fault indication lights are turned on at the fault time. Once the fault is removed the lights of the alarms go back to normal signal.

Mechanism to induce a fault in Simulation

To generate a fault in the Actual PV Plant, faults are enabled with set timings in GUI. These parameters are passed to the MATLAB workspace. The MATLAB

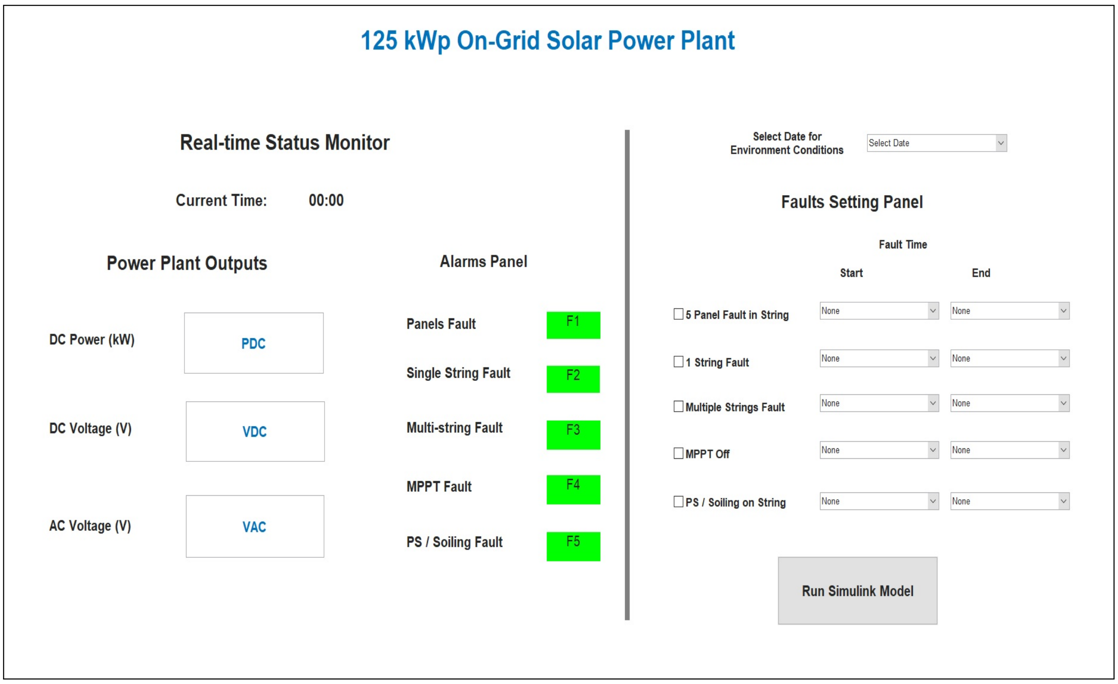


FIGURE 3.9: GUI for the simulation of PV power plant model. Left hand panel Real-time Status Monitor, right hand panel is Fault Setting Panel

function block receives fault type and its set timing during simulation and the fault conditions are set or disabled in model accordingly at the corresponding times.

- To generate the failure or short-circuiting of PV modules, number of PV modules in series of Simulink PV Component 'Series-connected modules per string' is changed during running of simulation to reduce the string size. This value gets normal once fault is removed.
- Similarly, in order to enable or disable single or multiple strings, constant value of one or zero is multiplied with the input irradiance and temperature to enable or disable the string.
- MPPT unit active or inactive is done in the same way, a constant one or zero is given input to a selector block which enables or disables the output of MPPT unit to control boost converter.
- Partial shading or soiling loss means less irradiance is being incident on the surface of PV module; therefore a gain is multiplied with the irradiance on

the string which reduces the irradiance representing partial shading or soiling effect on that particular string.

3.3 Fault Detection System

3.3.1 Principle of Proposed Fault Detection Algorithm

The proposed Fault Detection System uses an approach which is a bit similar to the one proposed by Dhimish [26]. Dhimish uses statistical approach which detects an abnormality in the PV plant and the ratios of Power and Voltage give the range to indicate what fault has occurred.

The principle of proposed algorithm is based on the Student's T-Test to detect the outlier in a given set of data [29], [30], [31]. The strings in Actual PV Plant which have different behavior compared to their respective counterparts in Theoretical PV system are pointed out.

Among the numerous applications of the T-Test method, outlier detection is one of them. Outlier detection enables the detection of an odd sample among as many samples as possible.

3.3.2 T-Test Statistical Tool

William Gosset's (Student's) T-Test statistical tool as used by Dhimish [26] is based on time average of several samples to find an outlier in the given samples. The outlier is a sample that differs from the rest of the samples. The T-test is popular in statistical applications where it is desired to test if two sets of data are different from each other or not.

The T-Test approach is easy for implementation and is perfectly applicable on any size of PV string and overall PV plant. The most common form of the formula to compute T-Test is:

$$T = \frac{\sqrt{n} \times (x - \mu)}{\sigma} \tag{3.1}$$

Where 'x' is the current sample, $'\mu'$ is the mean of samples, 'n' is the number of samples and 'σ' is the standard deviation [29].

The use of T-Test based approach to detect and identify the fault has made the system robust that faults are highlighted under any kind of weather conditions, irrespective of size of strings or complete PV array.

3.3.3 Z-Score, T-Score and String Power Ratios

The key difference of T-Test of Ref. [26] and the statistical tools proposed in this study is that the T-Test in equation 3.1 uses certain samples distributed at a known time interval; however, the proposed system uses somewhat a spatial approach. Samples of power of 21 strings is taken at a given instant of time to compute the T-Score and highlight the outlier. Another tweaking applied to the test method is that the mean and standard deviation to calculate the score is taken from the "Theoretical Plant'. This approach detects the fault whenever a string in Actual PV Plant has some abnormality as compared to the corresponding string in the Theoretical PV Plant model. The resultant of this test is called as Z-Score (or Z_Score) in this study and the formula for Z-Score is given as under:

$$Z\_Score(k) = \frac{P\_Str(k) - mean\_P\_Str\_Th}{stdev\_Th} \tag{3.2}$$

Where $'Z\_Score(k)'$ is the resultant score for k^{th} string in Actual PV Plant, which has power of $'P\_Str(k)'$ at the given instant of time. The mean value $'mean\_P\_Str\_Th'$ and $'stdev\_Th'$ are the mean and standard deviation of the 21 strings of Theoretical PV Plant at the same instant.

The T-Score value with mean and standard deviation of Actual Plant is computed which is used to locate if there are faulty PV modules in a string. The formula is given as:

$$T\_Score(k) = \frac{4 \times (P\_Str(k) - mean\_P\_Str)}{stdev} \tag{3.3}$$

Where $'T\_Score(k)'$ is the resultant score for k^{th} string in Actual Plant, which has power of $'P\_Str(k)'$ at the given instant of time. The mean value '$mean\_P\_Str'$ and '$stdev'$ are the mean and standard deviation of the 21 strings of Actual Plant at the same instant.

The power ratio is calculated on each string for identification of MPPT unit fault, i.e. ratio of each string of Theoretical Plant to the corresponding string of Actual Plant. The formula for string power ratio (PR_Str) is given as:

$$PR\_Str(k) = \frac{P\_Str\_Th(k)}{P\_Str(k)} \tag{3.4}$$

3.3.4 Faults and Limits of Mathematical Tools

The defined mathematical tools are used to identify the type of fault. All the faults are distinguished using different values of Z_Score, T_Score and PR_Str, some faults only require Z_Score to be diagnosed, whereas, some faults require second level of detection using T_Score and PR_Str for the accurate detection. The calculation of limits are explained as under.

PV Modules Failure (F1)

Consider the case of Reference PV Plant where there are 22 number of series-connected 270 W (30.61 V and 8.82 A) PV modules in one string. So, if some PV modules stop working, the string voltage will reduce eventually reducing the PV string power. When the string is working in normal conditions and no faulty PV modules are in the string, then ideally the string power should be 270 multiplied with 22 resulting in about 5.94 kW DC power and if one PV module is not working in the string, then the DC power will reduce to 5.67 kW. Further if the string gets affected with 10 of the faulty PV modules then the string DC power reduces to 3.24 kW.

These values of DC powers in case on 1 PV module and 10 PV modules is put in to the equation (3.2) and equation (3.3), which results in a range of values of Z_Score and T_Score to be in limits of 0 to -2600 and -9 to -25 respectively.

Single String or Multiple Strings Failure (F2 and F3)

Similar to PV modules failure, if a complete string stops working, then the DC power is zero. Computing the value of Z_Score under such condition yields the values below -2900. Further, a counter in the algorithm keeps a record of error on number of strings. The value of counter determines the number of strings under faulty condition.

MPPT Unit Failure (F4)

The MPPT unit failure affects the complete Actual PV Plant's DC voltage. To compute the values of mathematical operations, the value of DC voltage of 250 Volts because of fault is taken to calculate the DC power Actual PV Plant. This results in DC power of all strings to be 2.28 kW. The value of Z_Score and PR_Str of each string in such case comes out to be between range of -1150 to -850 and 1.22 to 2.4 respectively. F4count is compulsory to be equal to number of strings for the identification of MPPT fault, otherwise other faults may have occurred.

Partial Shading or Soiling Loss on a String (F5)

The partial shading or soiling loss is generated in the Actual PV Plant by reducing the input irradiance by factory or 0.6 for a PV string. As the irradiance has a direct effect on the DC power output of PV module, so in order to compute the values of mathematical operations the DC power of Actual PV Plant is reduced by same factor and then the values of Z_Score are found to be between range of -2600 to -850. If the F5count value is greater than 0 and less than number of strings then it is the partial shading or soiling fault, however if the F5count value is equal to number of strings then it is taken as MPPT unit fault.

The threshold values of Z_Score, T_Score and PR_Str for the studied faults are given in the Table 3.3.

TABLE 3.3: Ranges of Z_Score, T_Score and PR_Str for the Identification of Faults

Faults	Z_Score	T_Score	PR_Str
F1	$-2600 \leq Z \leq 0$	$-25 < T < -9$	-
F2	$Z < -2900$	-	-
F3	$Z < -2900$	-	-
F4	$-1150 < Z < -850$	-	$1.22 \leq P \leq 2.4$
	$-2600 < Z < -1150$	-	-
F5	$-2600 < Z < -850$	-	-

3.3.5 Algorithm and Flowchart of Fault Detection System

The algorithm of fault detection calculates the Z-Score at every 15 minutes time when the PV plants, both Actual and Theoretical, generate power. The Z-Score is located in certain ranges of values which define the type of fault. T-Score and PR-Str are also required to identify the faults of PV modules failure and MPPT unit failure respectively. The rules of fault detection are given as under:

- If $-2600 \leq Z\_Score(k) \leq 0$ and $-25 < T\_Score(k) < -9$, then increment F1count by one. If the value of F1count is greater than zero then at least one string has faulty PV modules in it.

- If $Z\_Score(k) < -2900$. When one sample has below –2900 of Z_Score value then F2count is incremented by one. If the F2count value is one then one string is faulty and if the value of F2count is more than one that means multiple strings are faulty.

- If $-1150 < Z\_Score(k) < -850$ and $1.22 \leq PR\_Str(k) \leq 2.4$, then F4count is incremented by one, if and only if the condition is fulfilled for all k, i.e. F4count = 21, then the MPPT unit has turned off or not working.

- If $-2600 < Z\_Score(k) < -850$, this range overlaps with the range used for MPPT fault detection. Second check is the F5count. If $0 < F5count < 21$, then there is partial shading on number of strings equal to the value of F5count. If F5count = 21 then this also correspond to MPPT unit fault.

Once a fault is detected the FDetect MATLAB Function sets the respective alarm flags and send signal to the GUI which displays the fault indication. The flowchart of simulation and fault detection system is presented in the Figure 3.10 below.

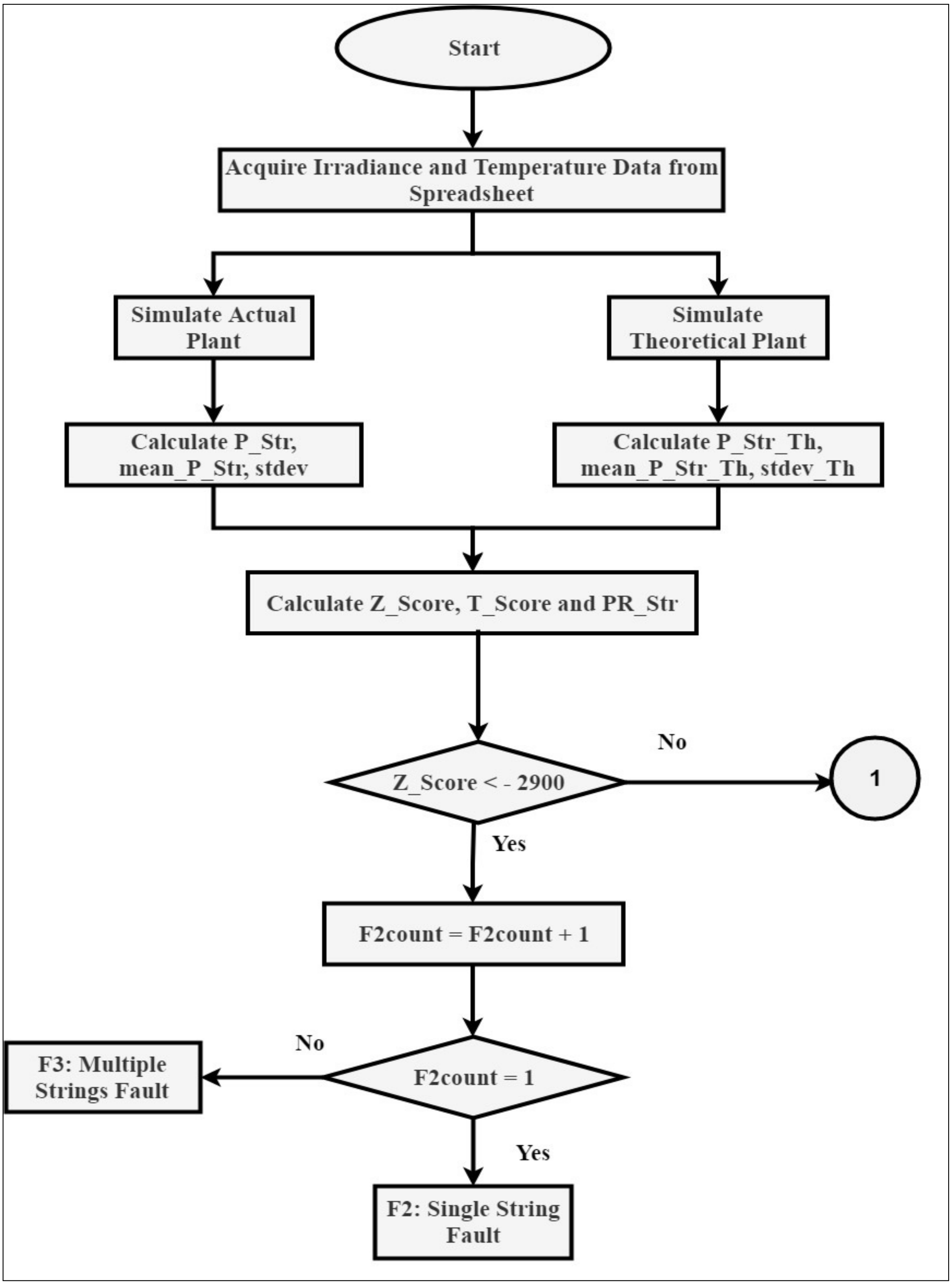
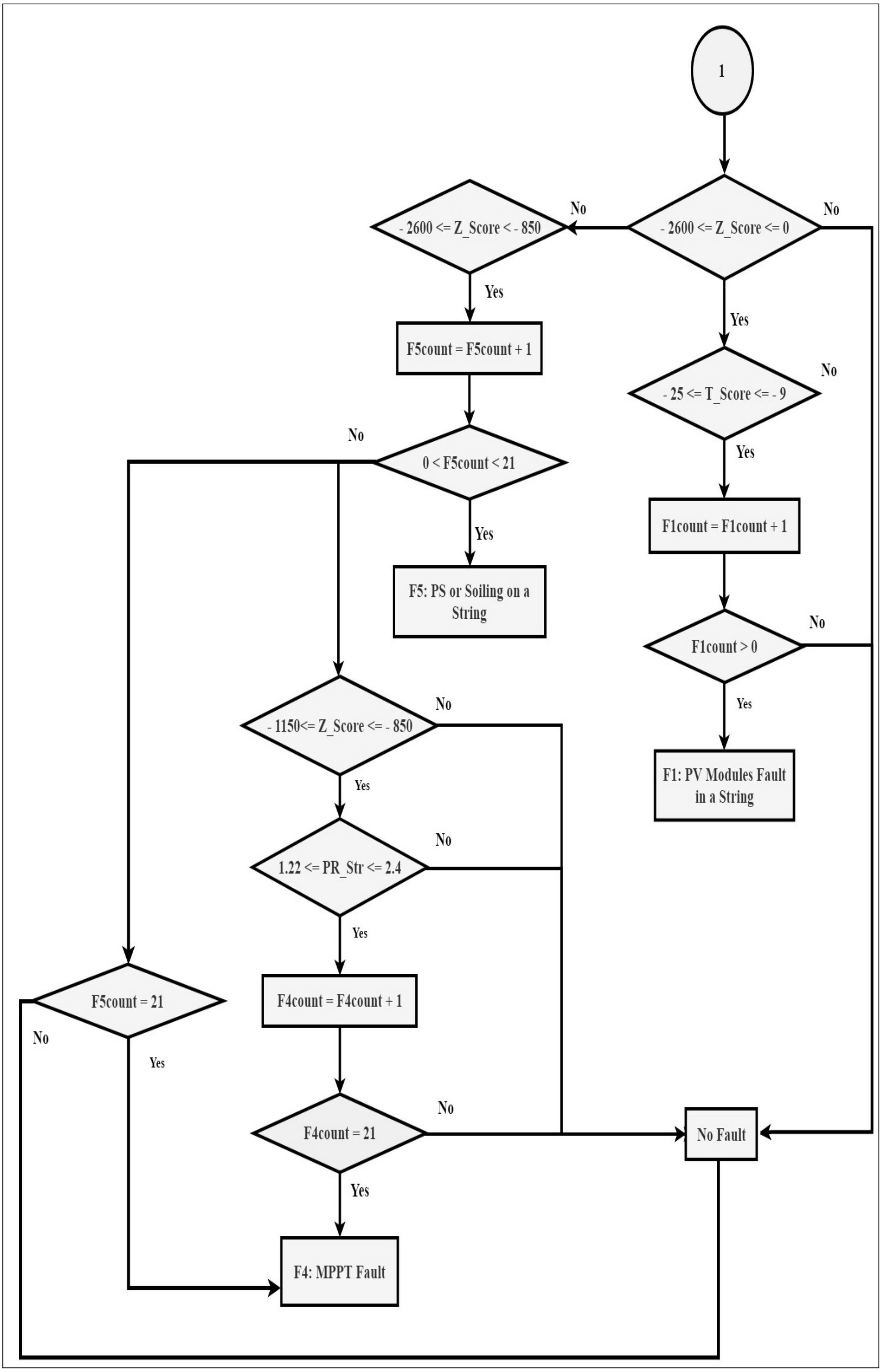


Figure 3.10: Flow Chart of Fault Detection System
(continued on next page)



(continued) Flow Chart of Fault Detection System

This fault detection system is implemented in the Simulink using MATLAB script coding in the function block. The voltages and currents of both Actual and Theoretical PV Plants are passed to the function block where script coding implements the algorithm of fault detection and identification. Z_Score, T_Score and PR_Str for all strings are calculated at time instants at 15 minutes intervals when irradiance and temperature information is given from the environment monitoring unit. The alarms for all faults are passed on to the GUI for indication of these faults.

This chapter explained the details of reference power plant and modeling of the reference plant as Theoretical Plant in the MATLAB® R2018a. The chapter concluded with presenting the fault detection algorithm. The next chapter evaluates the performance of fault detection system under various weather conditions. The chapter ends with discussion of fault detection system.

Chapter 4

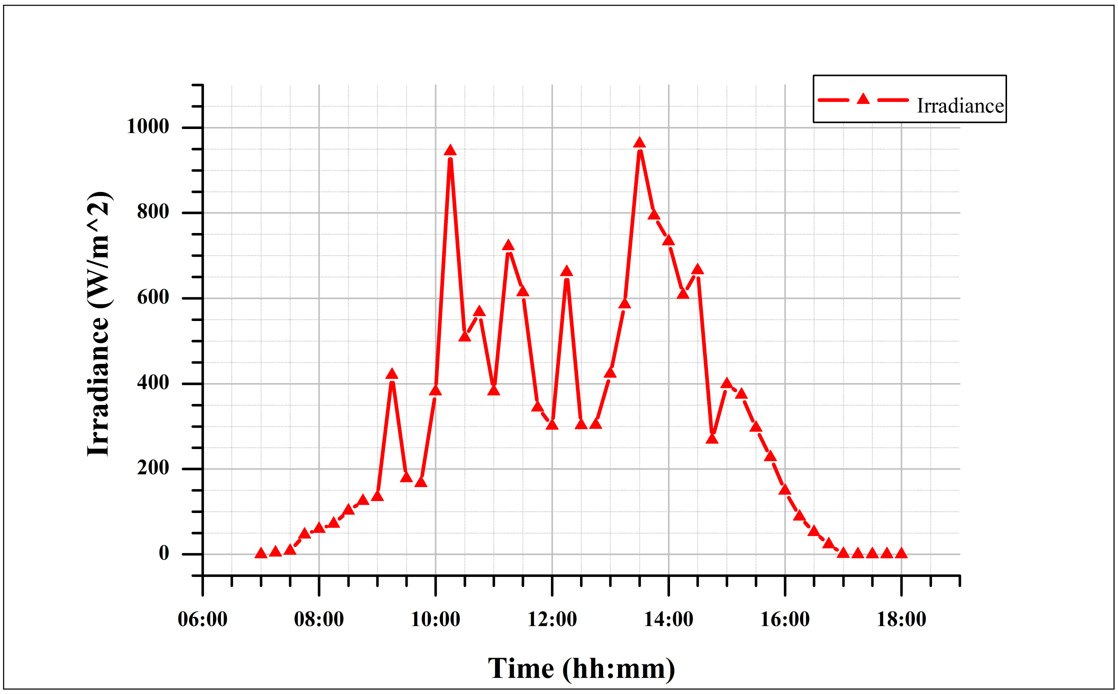
Results Evaluation and Discussion

This chapter presents the simulation results of the modeled PV power plant with faults induced at different time intervals and different weather conditions. Faults are set on different days to see the results the fault detection system. Later, it is discussed what are the benefits and limitations with the proposed algorithm and complete fault detection system.

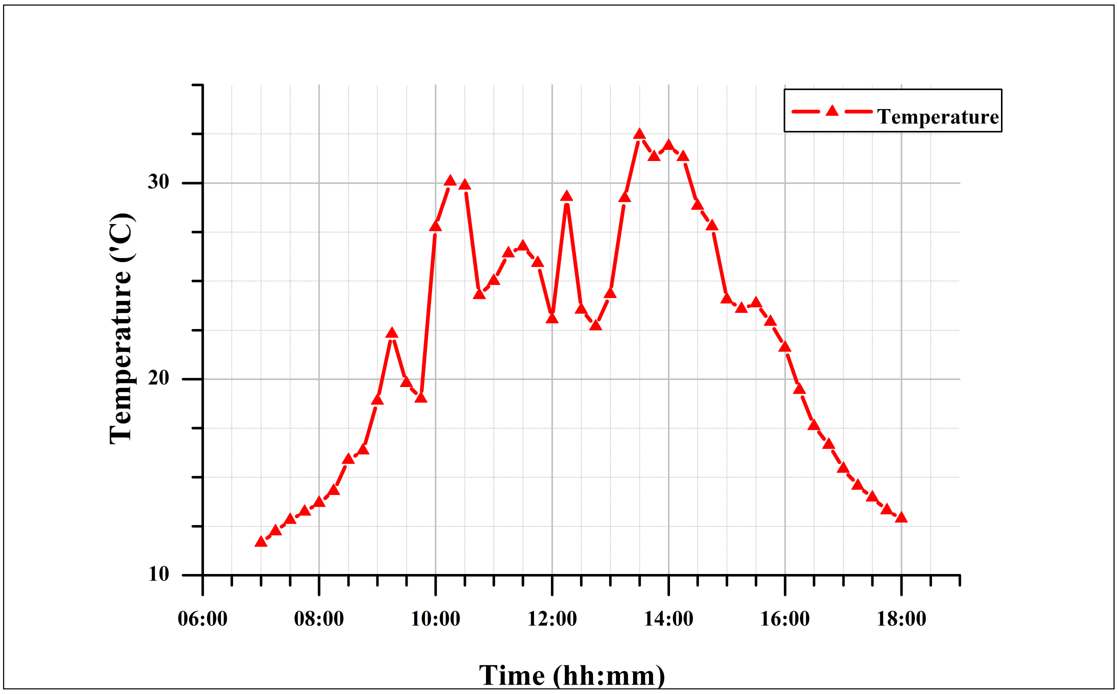
4.1 Simulation of Modeled Grid-tied PV Plant

In order to analyze the test results proposed fault detection system, it is important to examine the DC power outputs of the reference PV plant to confirm that the modeled PV plant has very similar behavior at the DC side. This is required because if the Theoretical PV Plant output does not match closely with Reference PV Plant then algorithm may indicate faults in normal conditions as well. To compare the DC power of reference PV plant and the simulated PV plant, screenshots of graphs of PV power from local monitoring system of reference PV plant are obtained.

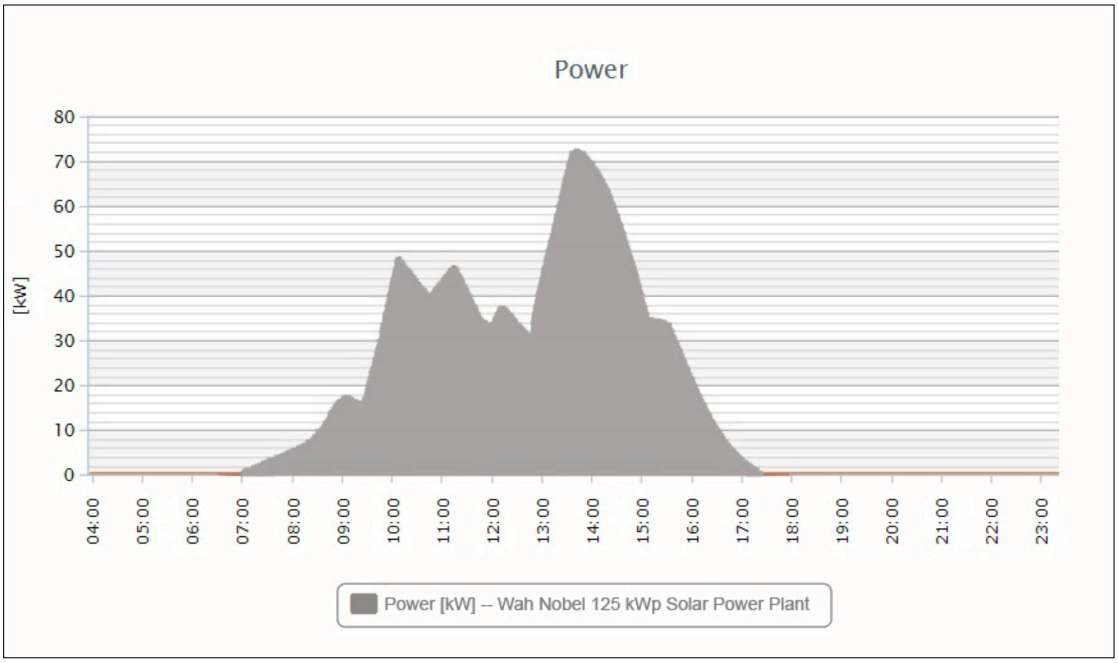
Figure 4.1 (a–d) presents irradiance and PV module temperature of one full day and DC Power graph of reference PV plant and simulated PV plant under these conditions.



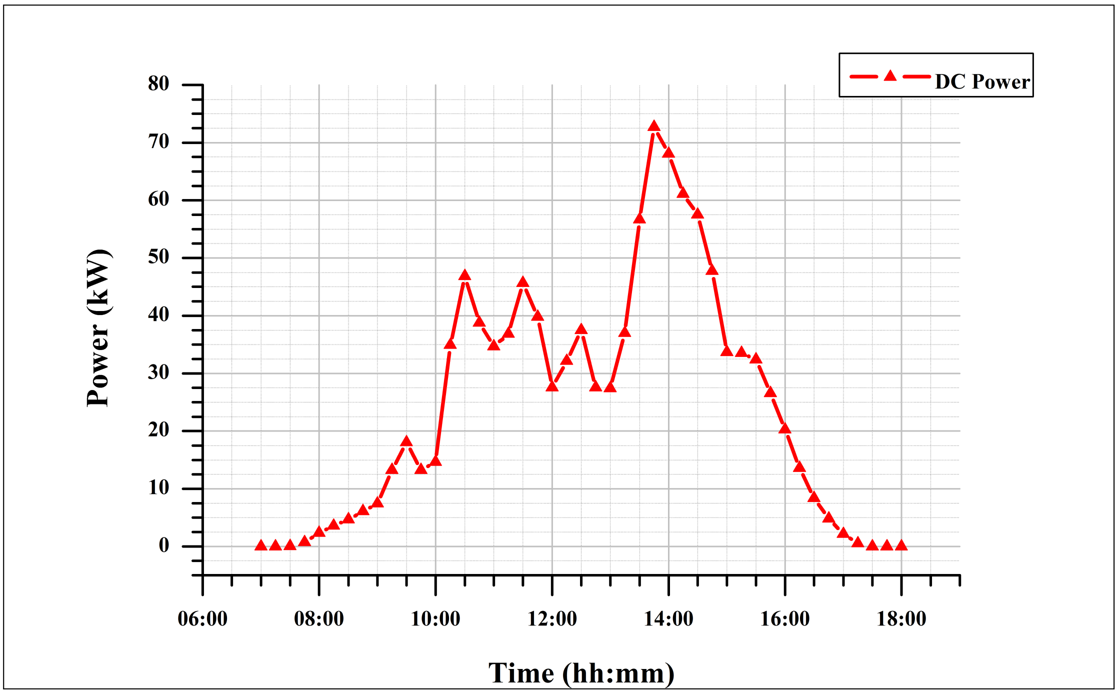
(a) Irradiance on Full Day to Compare DC Power Output of Reference and Simulated PV Plants



(b) Temperature on Full Day to Compare DC Power Output of Reference and Simulated PV Plants



(c) DC Power Output of Reference PV Plant (Screenshot from Monitoring System of Reference Plant)



(d) DC Power Output of Simulated PV Power Plant

Figure 4.1: Comparison of Power Outputs of Reference and Simulated PV Plants

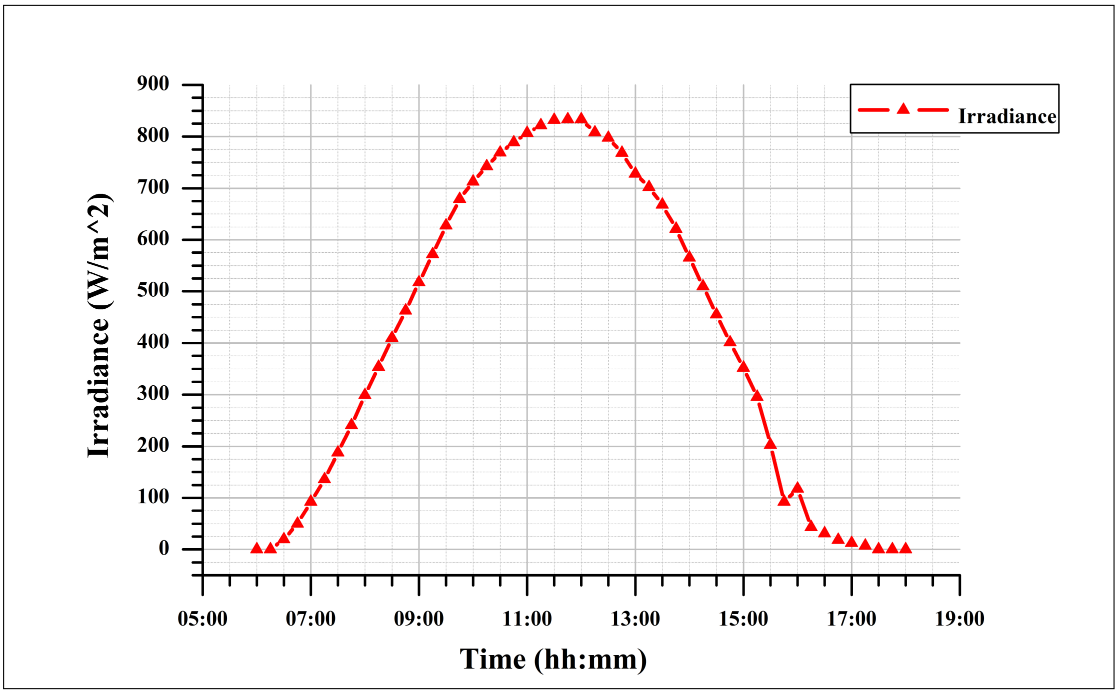


FIGURE 4.2: Plot of Irradiance Measured at 15 Minutes Intervals on Test Day – 1

4.2 Results Evaluation

The fault detection system has been run through weather conditions of two different days, the results obtained for these days dated 21st October and 12th November 2018 are presented in following subsections.

4.2.1 Test Day – 1

The irradiance and temperature of first test day, dated 21st October 2018, are shown in the Figure 4.2 and Figure 4.3 respectively. The weather remained sunny throughout the day and a peak of 833 W/m^2 of irradiance was recorded. Highest temperature in the day was 40°C.

Three faults were introduced in the Actual PV Plant. These faults, their location in the PV system and timings are mentioned in the Table 4.1. The simulation of PV plants and faults begins after setting date and faults in the GUI shown in Figure 4.4.

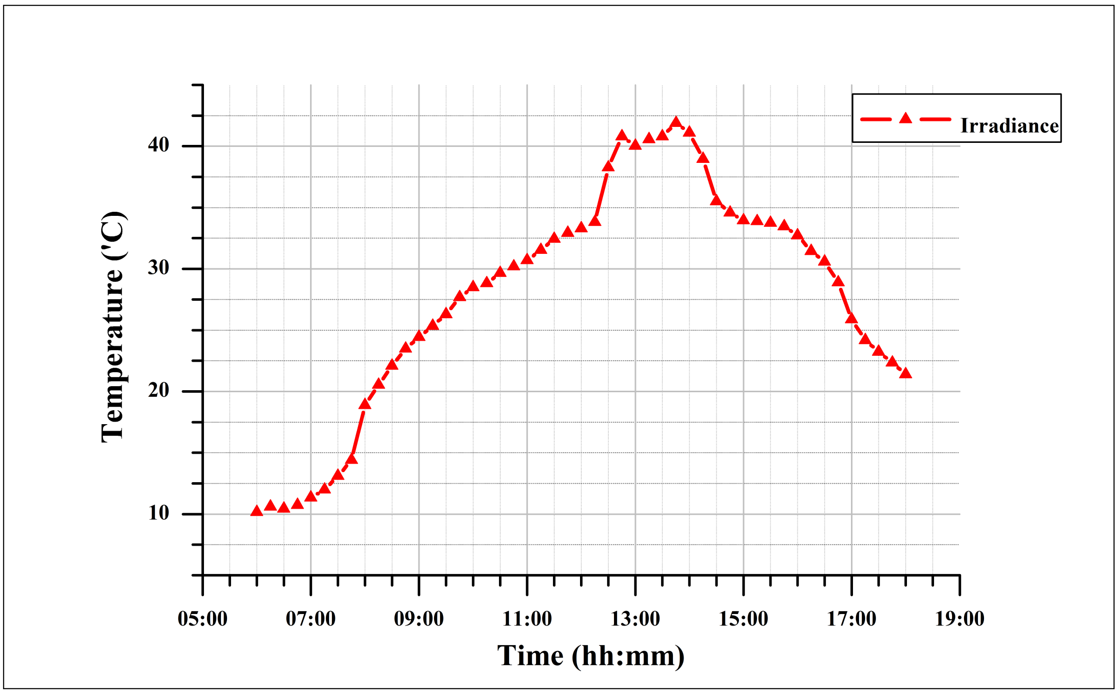


FIGURE 4.3: Plot of PV Module Temperature Measured at 15 Minutes Intervals on Test Day – 1

TABLE 4.1: List of Faults in the Actual PV Plant on Test Day – 1

Sr.	**Fault Type**	**Fault Location**	**Time of Fault (hh:mm)**
1	PV Modules Fault in a String	String 2	09:00 – 10:30
2	Single PV String Fault	String 3	12:00 – 13:00
3	MPPT Fault	Complete PV Array	14:00 – 16:00

The 'Real-time Status Monitor' on the GUI highlighted the faults as per the set time after processing the Actual PV Plant data. At intervals of 15 minutes, the simulation receives irradiance and temperature value and corresponding power of all strings are passed to the fault detection system. The fault detection system runs its algorithm and finds the faults correctly as set before the simulation.

The Figure 4.5 shows the 'Real-time Status Monitor' displaying the alarms of the faults during the simulation.

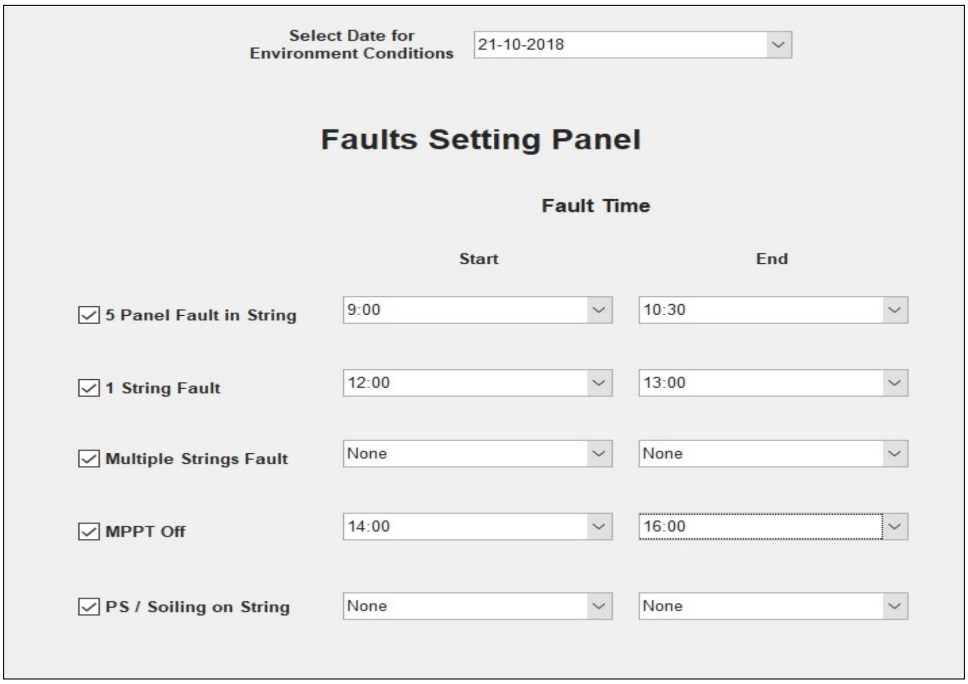
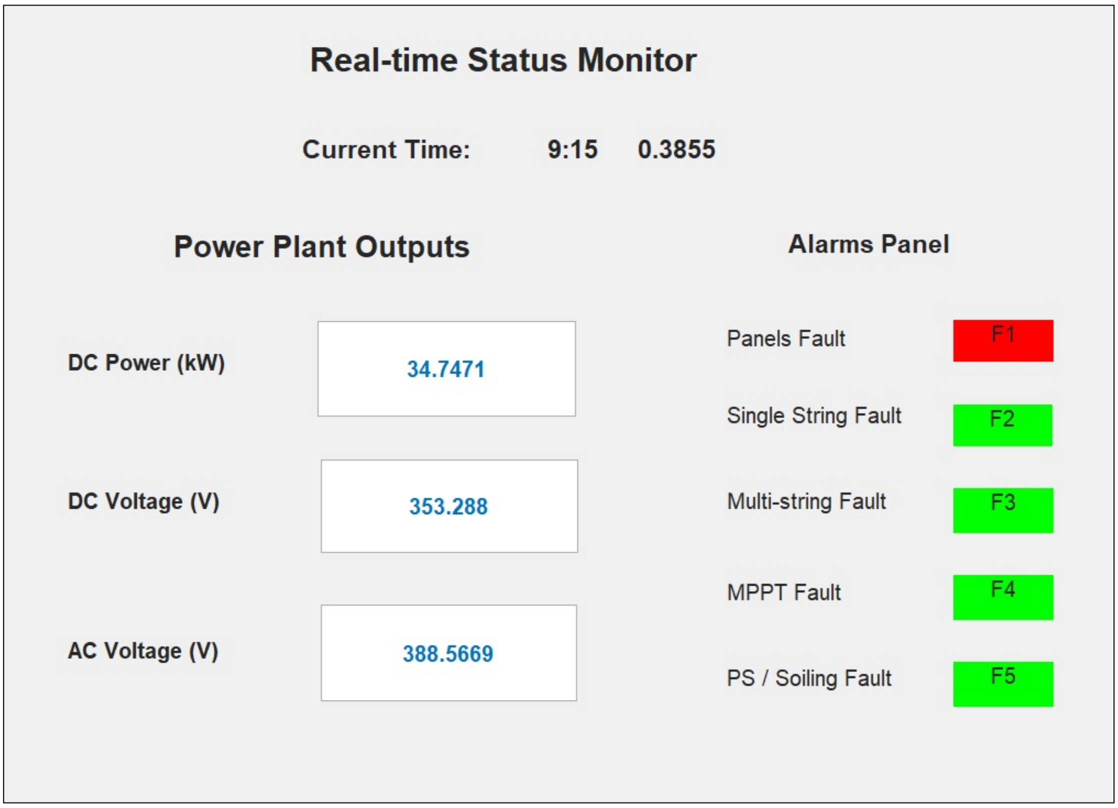
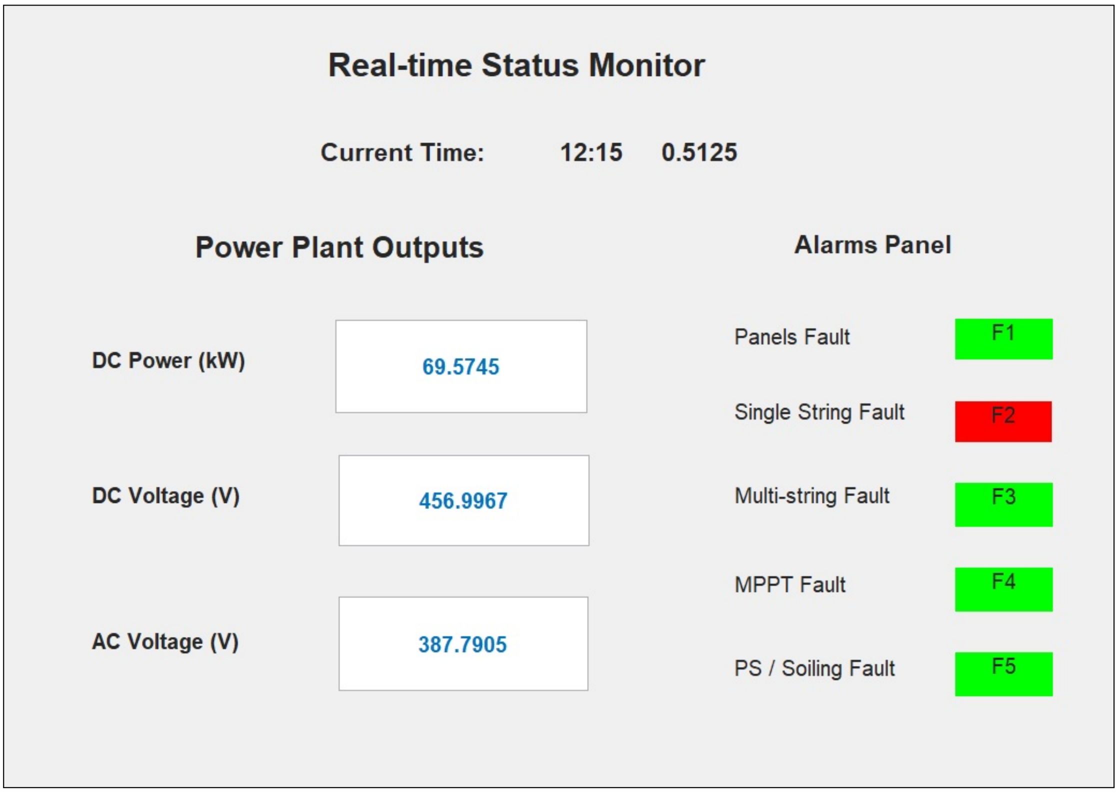


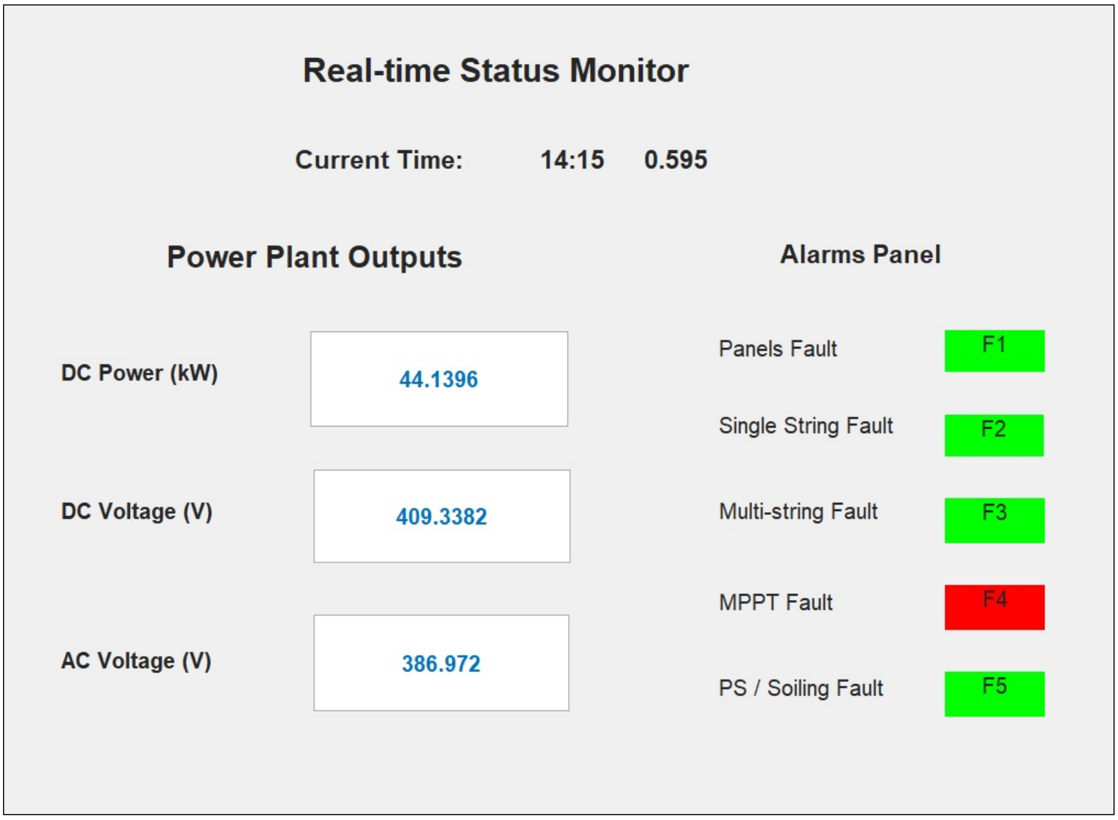
FIGURE 4.4: Setting of Faults in the GUI for Simulation on Test Day – 1



(a) Alarm Indication for PV Modules Fault (F1)



(b) Alarm Indication for Single String Fault (F2)



(c) Alarm Indication for MPPT Unit Failure (F4)

FIGURE 4.5: Indication of Faults in the Real-time Status Monitor GUI on Test Day – 1

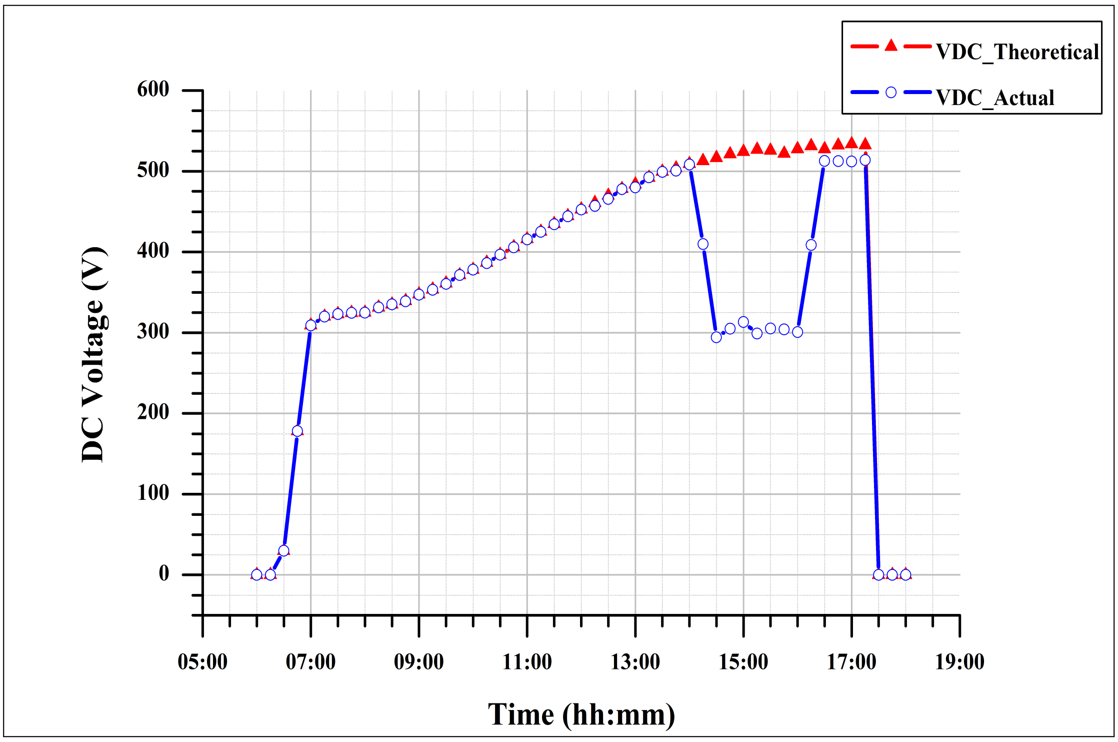


FIGURE 4.6: Comparison of DC Voltage of Theoretical and Actual PV Plants under the Influence of Fault 1, Fault 2 and Fault 4 on Test Day – 1

The variations between the voltage and power of Actual PV Plant and Theoretical PV Plant show the effects of these faults and how the power degrades when such faults occur in the PV power plants. The comparison of voltage and power output of Actual and Theoretical PV plants is pictured in the Figure 4.6 and Figure 4.7 respectively.

It is clearly visible there are reasonable deviations in the power output when the 1 string fault is occurred at 12:00 and when the MPPT fault arises at 14:00. It can be seen in the Figure 4.7. The PV module fault is not visible in the power outputs, however, this fault is clearly detected with help of the proposed algorithm.

Based on the algorithm, we can analyze the results of the fault detection system and the performance of the algorithm under the applied conditions. The calculation of *Z_Score*, *T_Score* and *PR_Str* are done by the system and their values for all strings are collected.

The *Z_Score*, *T_Score* and *PR_Str* during the fault times and for the affected strings are shown in Figure 4.8, Figure 4.9 and Figure 4.10 respectively.

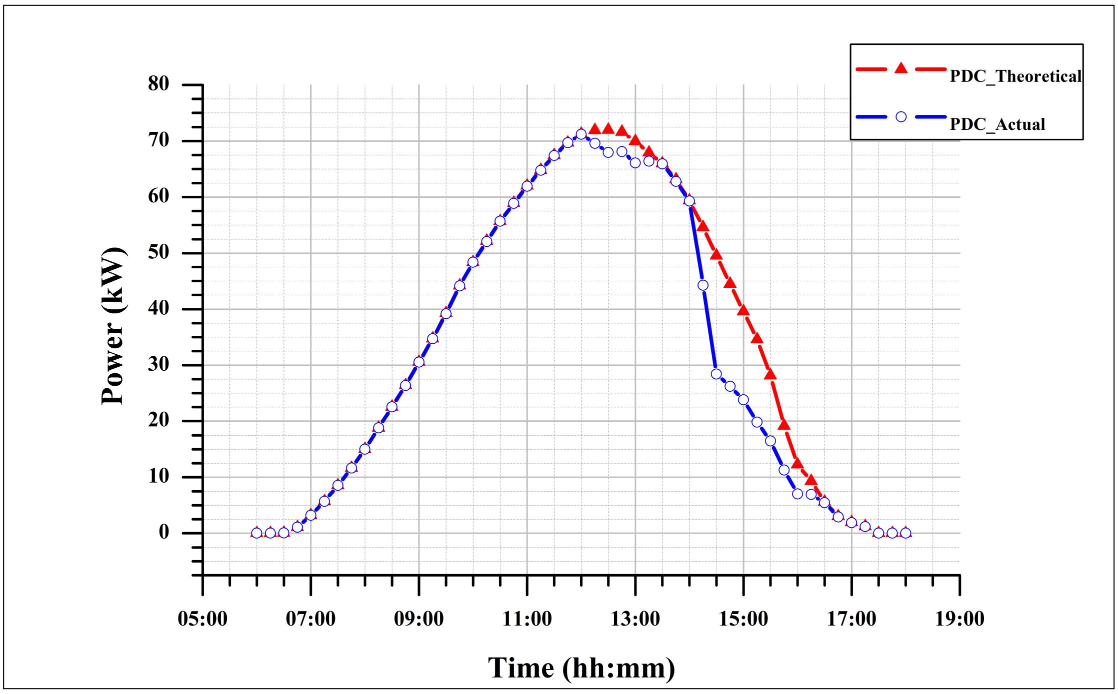


FIGURE 4.7: Comparison of DC Power of Theoretical and Actual PV Plants under the Influence of Fault 1, Fault 2 and Fault 4 on Test Day – 1

Type 1 Fault

When the Type 1 Fault occurs in string 2 of Actual PV plant from 09:00 hours to 10:30 hours, the *Z_Score* of all strings ranges between the values of –63 to 56. This condition takes to the inspection of *T_Score*. *T_Scores* of all strings are checked and the value for string 2 comes out to be ranging around -16 during this time.

It can be seen in Figure 4.8 that the *Z_Score* during this time is within the range of –2600 to 0 then we need to look for *T_Score* at the corresponding time shown in Figure 4.9. The *T_Score* is less than –9 and higher than –25. This indicates the PV modules failure. The *Z_Score* deviation was observed on the String number 2, so it can be concluded that there is F1 fault on the string 2.

Type 2 Fault

At 12:00 hours, the system encounters value of *Z_Score* for string 3 to be less than –3200. This drop in value of *Z_Score* remains till 13:00 hours time, whereas the rest of strings are not showing such drop in the values of their respective *Z_Scores*. *Z_Score* of –3200 is far less than –2900 then it means the fault is either a single

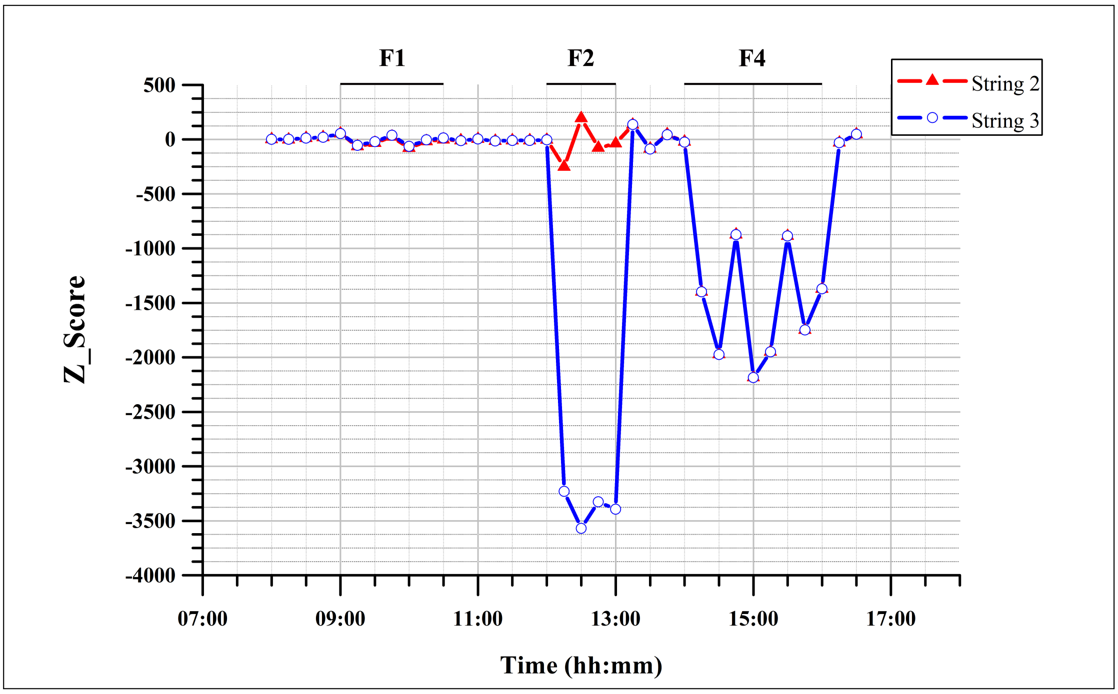


Figure 4.8: *Z_Score* for String 2 and String 3 Affected by the Faults on Test Day – 1

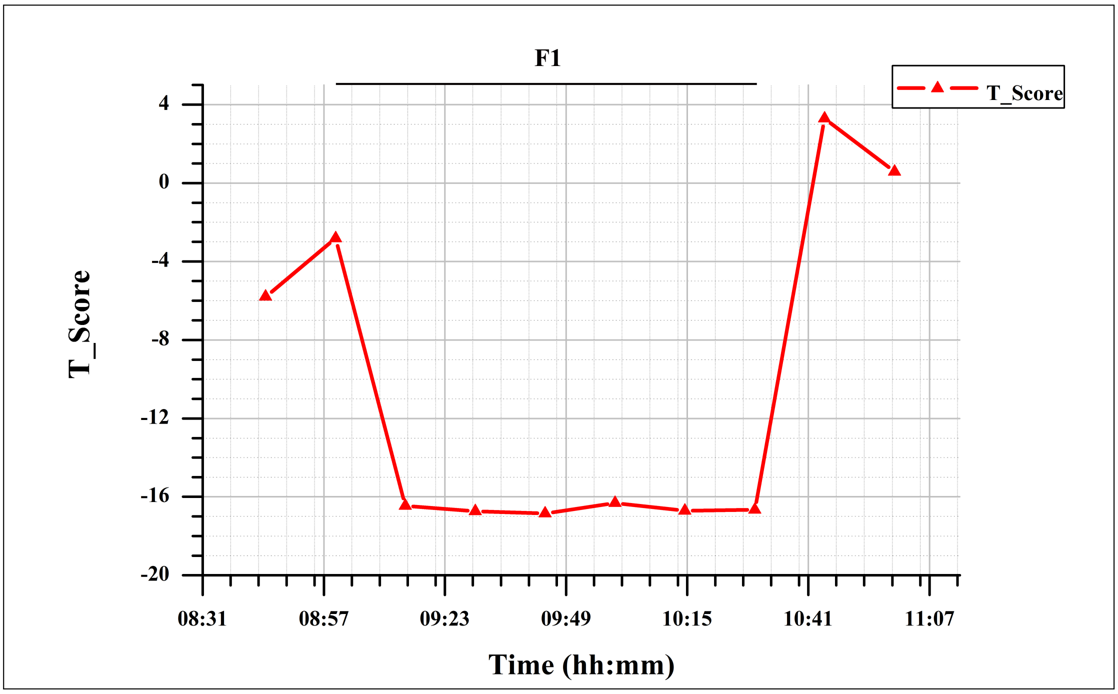


Figure 4.9: *T_Score* for String 2 Indicating Faulty PV Modules (F1) during Plotted Time on Test Day – 1

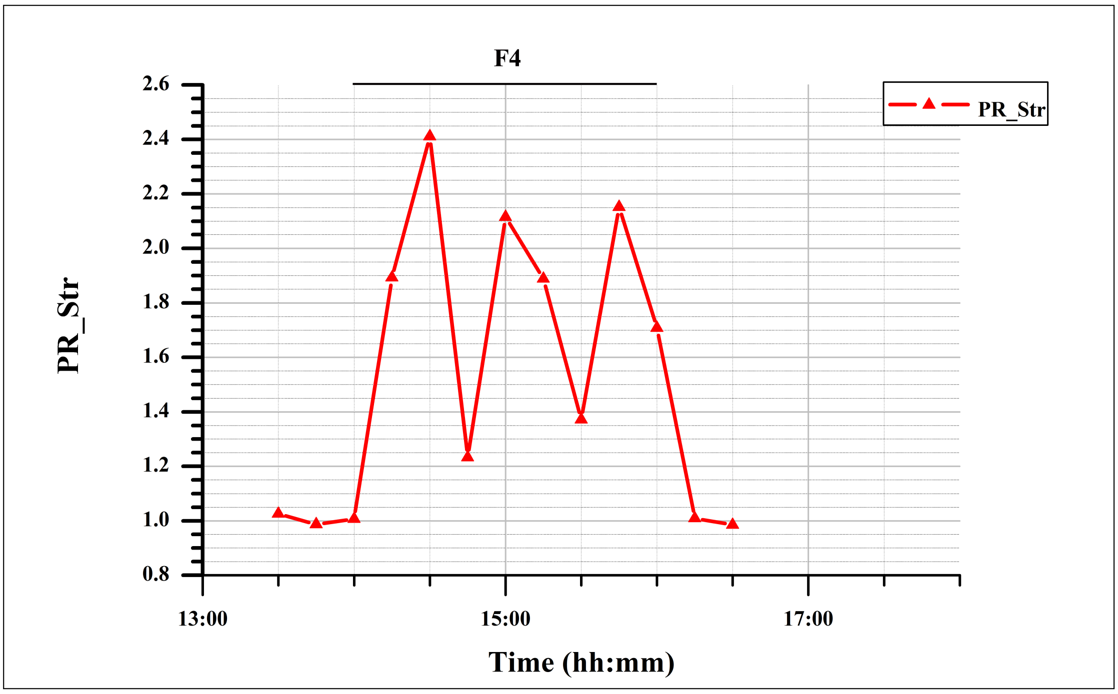


FIGURE 4.10: Strings Power Ratio (*PR_Str*) when *Z_Score* Value Ranged between –1150 to –850 to Indicate MPPT Unit Fault (F5) on Test Day – 1

string or multiple strings failure. The system internally processes the final value of F2count. The F2count is equal to 1. This highlights the single string fault. *Z_Score* of all strings is examined and only one string was the outlier so that string is pointed out to be faulty.

Type 4 Fault

At 14:00 hours, the *Z_Score* value for all strings has dropped to –1400 and reaches up to –2180. It is to be noted that the *Z_Score* is in the range of -2600 and -850, then the F5count is checked to be 21. This corresponds to the range for MPPT unit failure fault. Here ranges of *Z_Score* are not directly falling under the MPPT range but when the F5count is equal to 21 then such fault is not the partial shading but MPPT fault as per the algorithm.

4.2.2 Test Day – 2

12th November 2018 is the second day selected for the results evaluation. This day had a very fluctuating pattern in irradiance due to cloudy conditions. The irradiance had multiple ups and downs resulting in deviations in the temperature pattern as well at the corresponding times. This weather condition is one of the crucial conditions that can be applied to test the performance of the fault detection algorithm.

The rapid and abrupt changes in the weather conditions cause power output deviations of the PV array. The modeled PV plant's output behavior matched very much with the output of the reference PV plant. This provides evidence to the accurate modeling of the PV plant and further enhances the credibility and proper functioning of the proposed fault detection system for large scale PV power plants. The irradiance and PV module temperature are shown in Figure 4.11 and Figure 4.12 respectively.

Considering it an interesting and one of the complicated scenarios to test the fault detection system, all the implemented faults were induced in the Actual PV Plant. The sequence of faults has been set such that partial shading is appeared first, followed by multiple strings fault, MPPT unit fault, single string fault and finally the PV modules fault.

The type of faults and their time of occurrence is shown in the Table 4.2 and the same are set in the GUI as shown in Figure 4.13. The results as appeared on the GUI during simulation are shown in Figure 4.14.

The outcomes of the simulation and fault detection system are acquired for evaluation. It is seen from the voltage and power plots of Theoretical and Actual PV Plants that there have been abnormalities in the Actual PV Plant at the times set for the faults. The curves of DC voltage and power of both PV plants are shown in the Figures 4.15 and 4.16 respectively. The fault occurrence in the Actual PV Plant can be seen from the DC power and voltage graphs.

The differing behavior is diagnosed with the help of the proposed statistical operations Z_Score, T_Score and the string power ratio PR_Str, shown in Figures 4.17, 4.18 and 4.19 respectively. The accurate fault detection and correct identification is evident from the values of these operations.

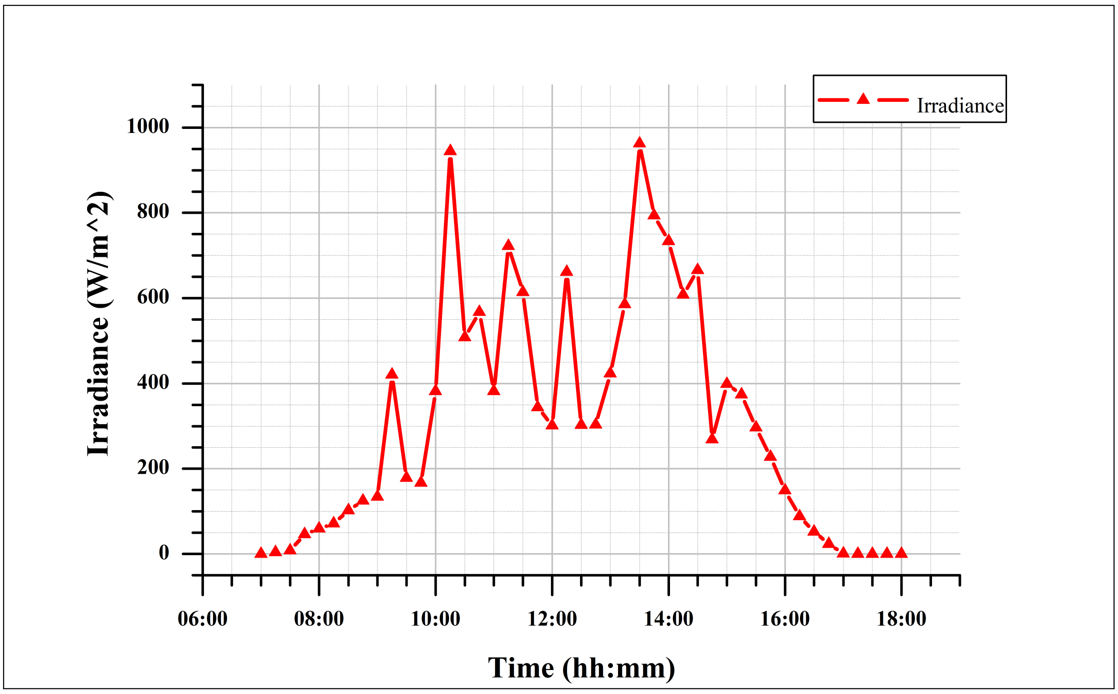


FIGURE 4.11: Plot of Irradiance Measured at 15 Minutes Intervals on Test Day – 2

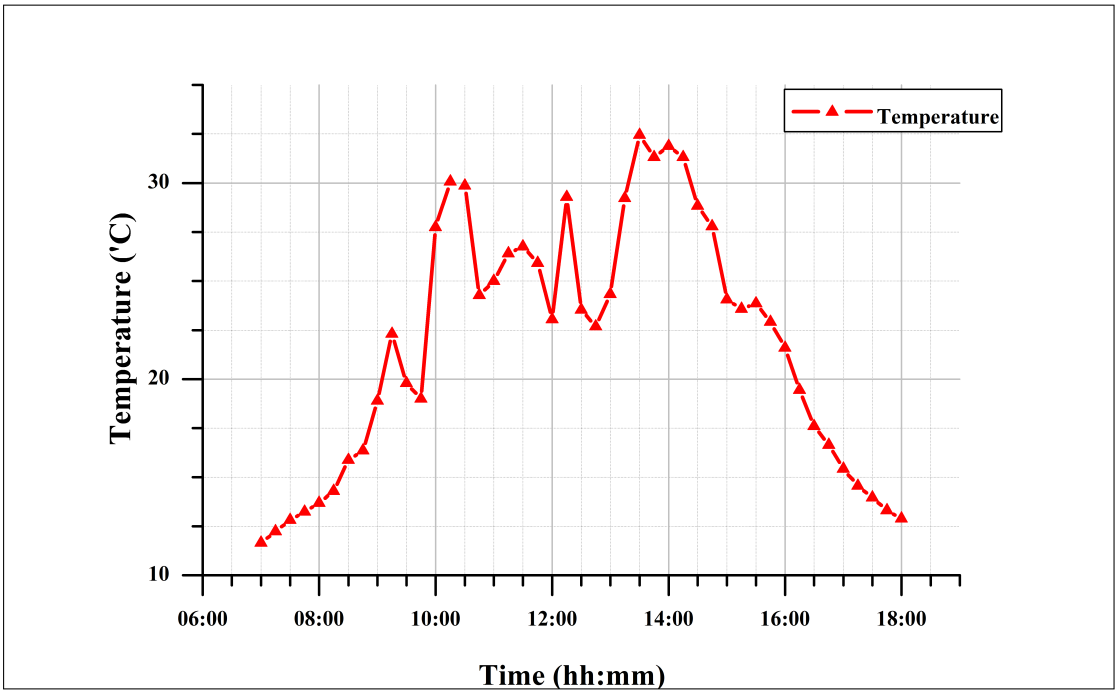


FIGURE 4.12: Plot of PV Module Temperature Measured at 15 Minutes Intervals on Test Day – 2

Table 4.2: List of Faults in the Actual PV Plant on Test Day – 2

Sr.	Fault Type	Fault Location	Time of Fault (hh:mm)
1	Partial Shading / Soiling	String 1	08:30 – 09:45
2	Multiple PV String Fault	String 4, 5 & 6	10:30 – 11:30
3	MPPT Fault	Complete PV Array	12:00 – 13:00
4	Single PV String Fault	String 3	14:00 – 15:00
5	Faulty PV Modules in a String	String 2	15:30 – 16:30

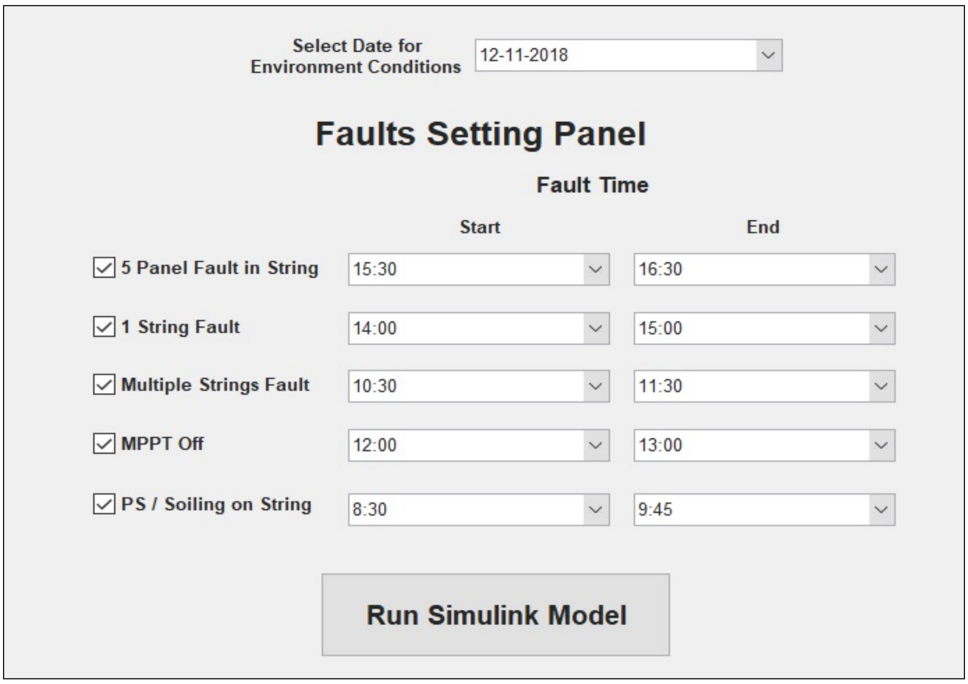
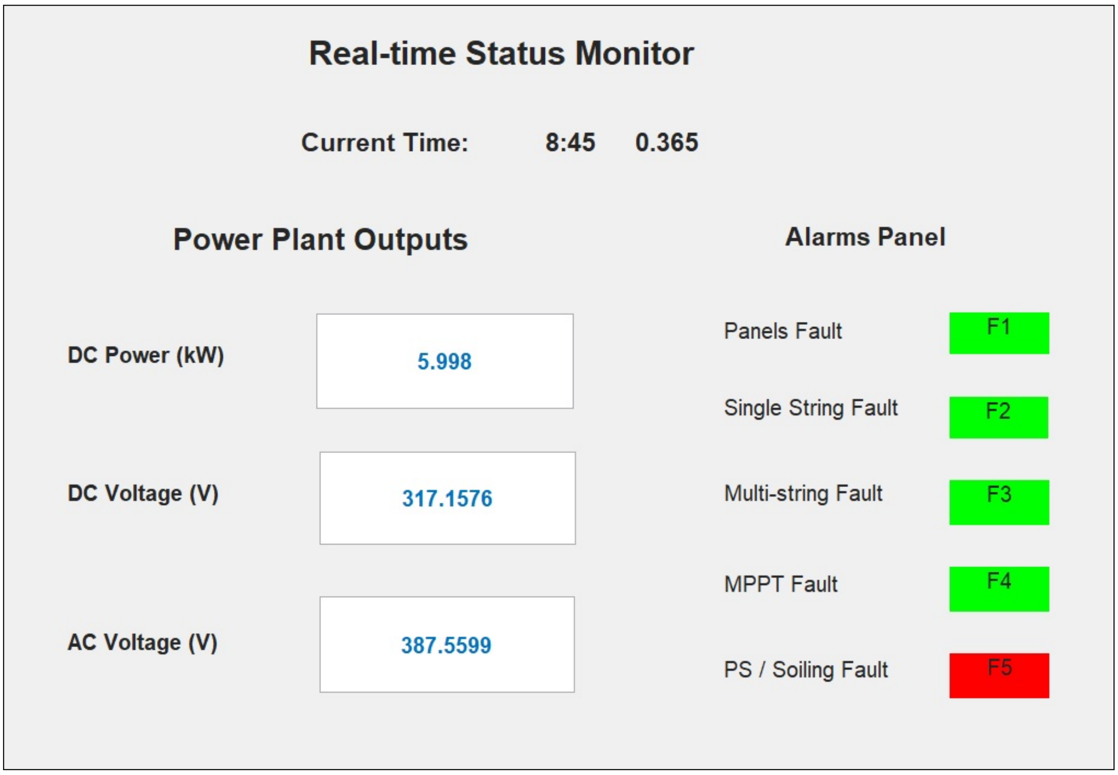
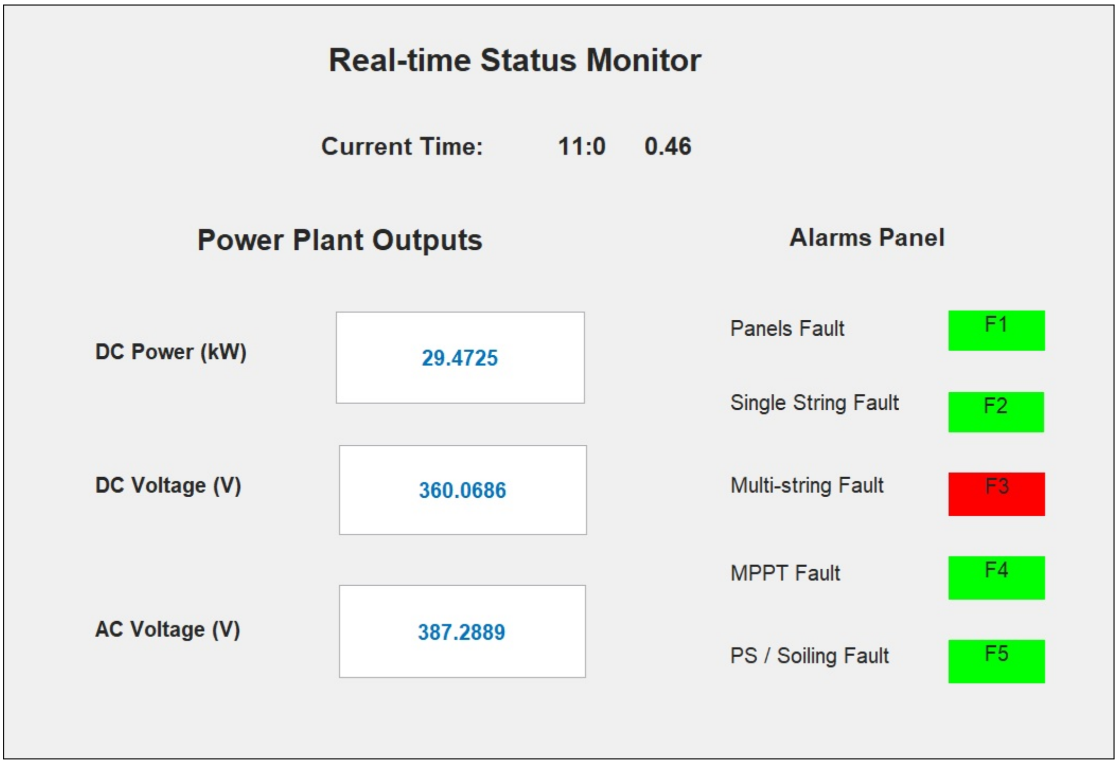


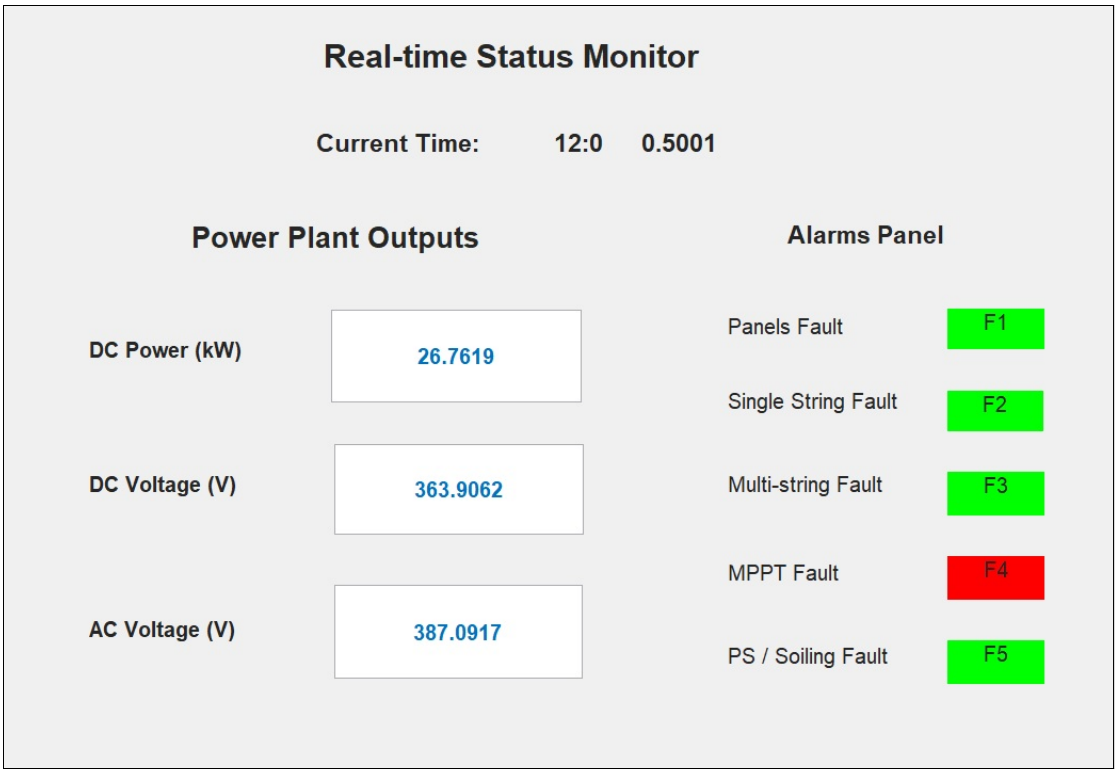
Figure 4.13: Setting of Faults in GUI on Test Day – 2



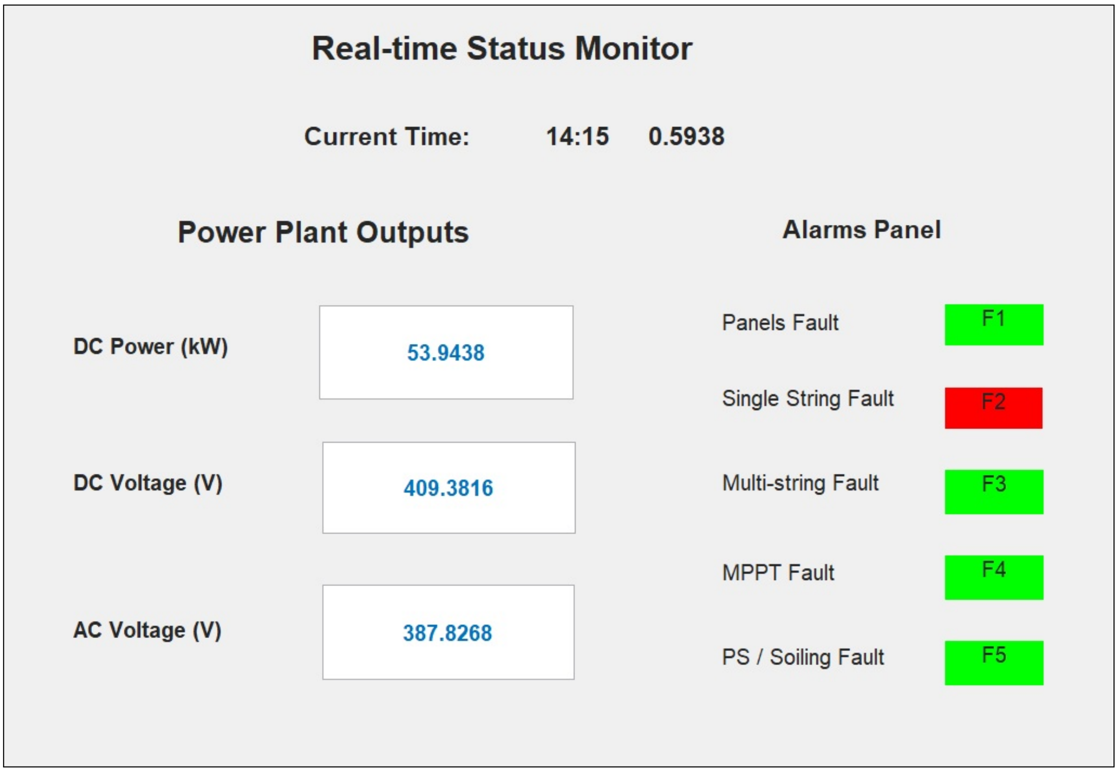
(a) Alarm Indication for Partial Shading / Soiling (F5)



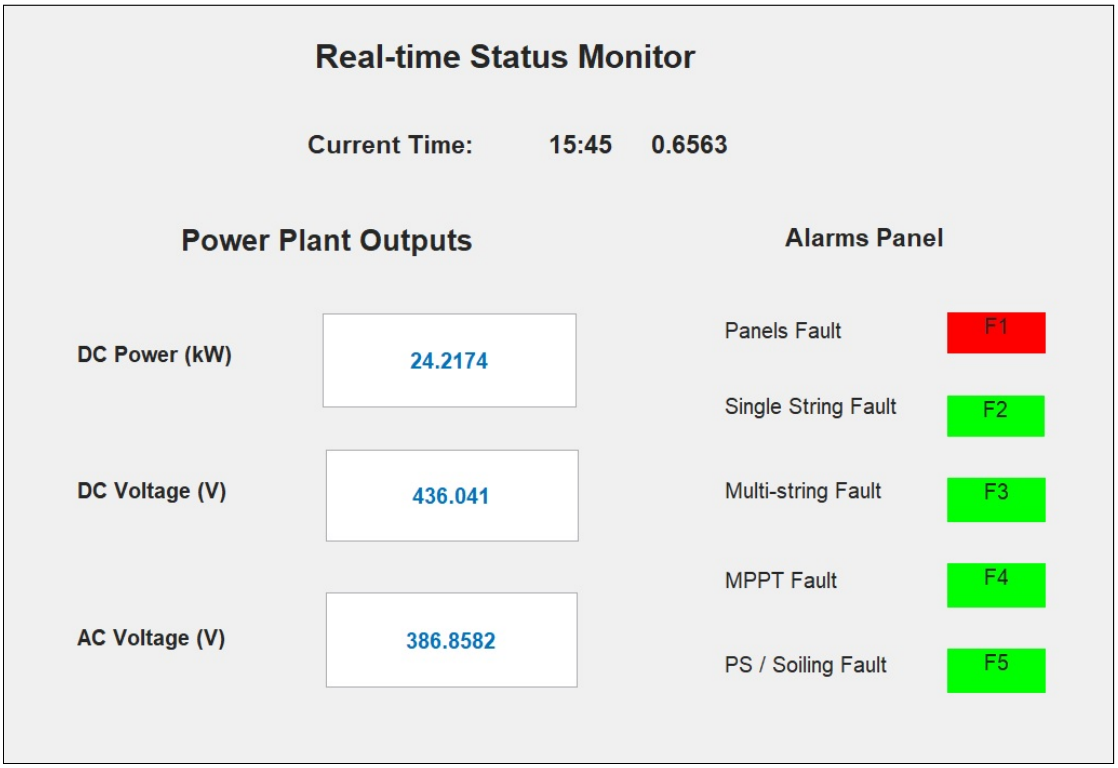
(b) Alarm Indication for Multiple Strings Fault (F3)



(c) Alarm Indication for MPPT Fault (F4)



(d) Alarm Indication for Single String Fault (F2)



(e) Alarm Indication for Faulty PV Modules (F1)

FIGURE 4.14: Indications of Fault Alarms in the Real-time Status Monitor on Test Day – 2

Type 5 Fault

At time 08:30 to 09:30, the *Z_Score* is falling under the range of –2600 to –850, then the algorithm looks for the F5count. The F5count here is 1 so this is the Partial Shading or Soiling Loss on 1 string fault.

Type 3 Fault

At 10:30 to 11:30, the *Z_Score* is less than –2900, which implies it is either the 1 string fault of multiple strings fault. So the F2count is examined which is equal to 3, hence multiple strings fault is diagnosed. Obtaining the value of k identifies that fault is in the String number 4, 5 and 6.

Type 4 Fault

At 12:00 to 13:00, the *Z_Score* has ranged between –1070 to –1195, then the *PR_Str* is checked. The value of *PR_Str* is between 1.22 to 2.4 and finally the F4count is equal to 21. This means this is the MPPT unit fault.

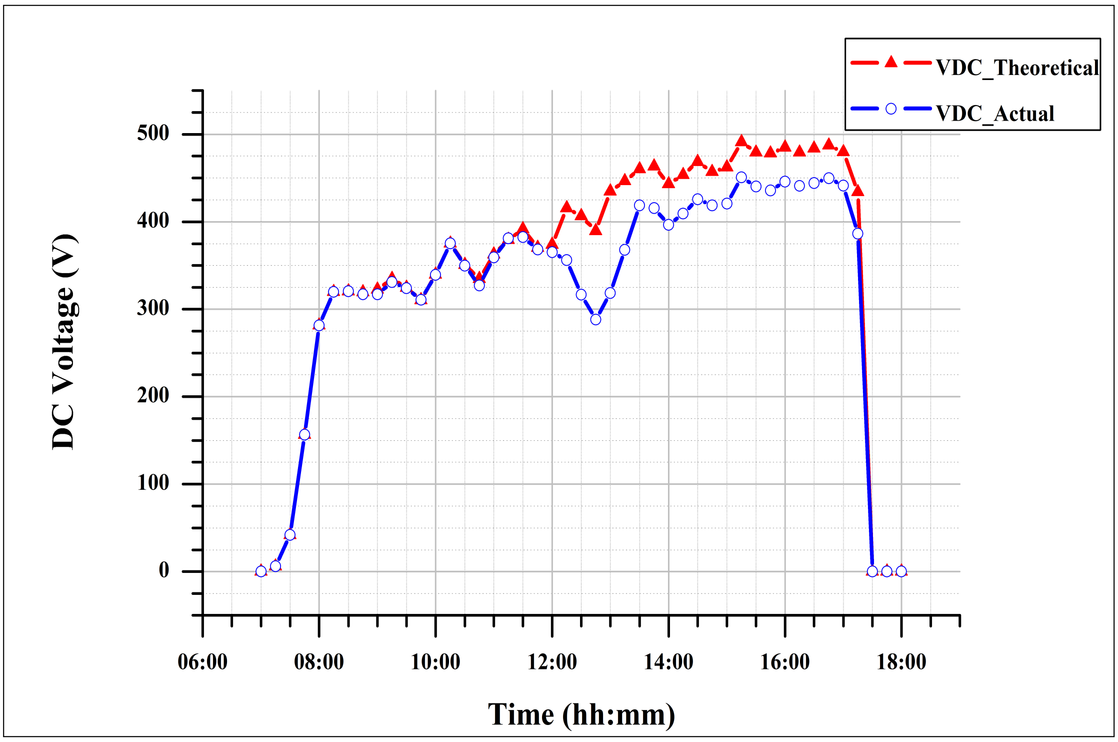


FIGURE 4.15: DC Voltage of Theoretical and Actual PV Plants on Test Day – 2

Type 2 Fault

At 14:00 to 15:00, the *Z_Score* again falls below –2900, the F2count is 1 here. So the fault is 1 string failure and string number is 3.

Type 1 Fault

At 15:30 to 16:30, the *Z_Score* on String 2 is between –2600 to 0, the *T_Score* on this time interval is between –17 to –5, so it is diagnosed that there are faulty PV modules in the String 2.

4.3 Discussion on Fault Detection Algorithm

As studied in the previous section, the faults on PV power plant as defined in this study are being detected and properly identified. The fault detection system, proposed in this study, is quite simple and easy in terms of implementation on existing PV plants and it can be used with various sizes of PV power plants.

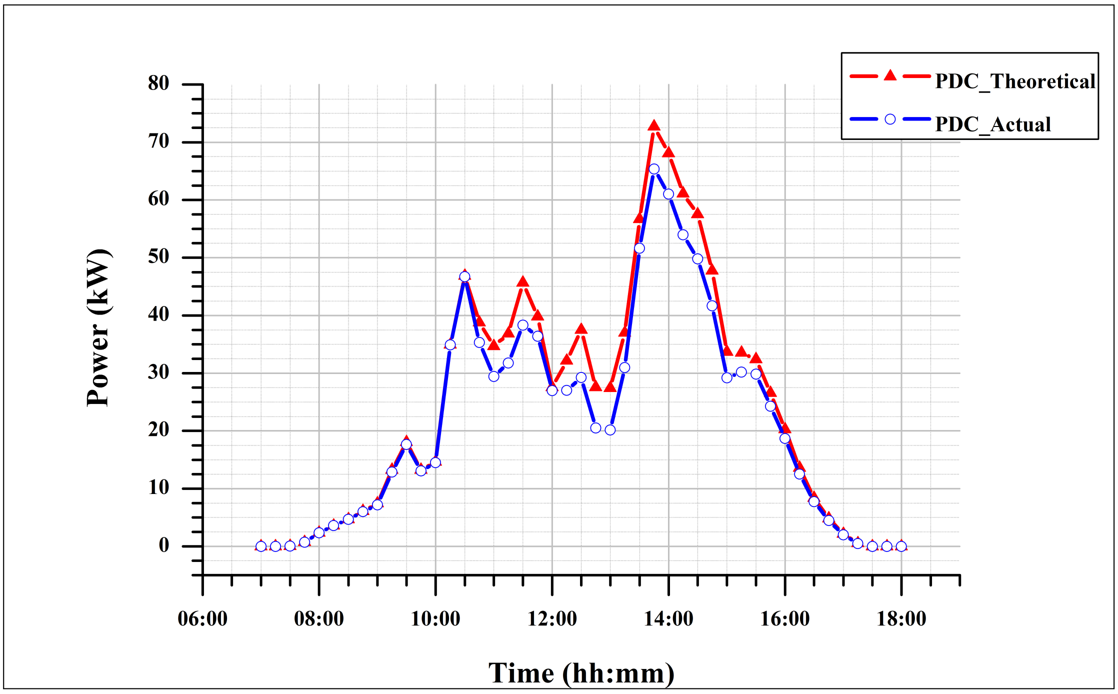


FIGURE 4.16: DC Power of Theoretical and Actual PV Plants on Test Day – 2

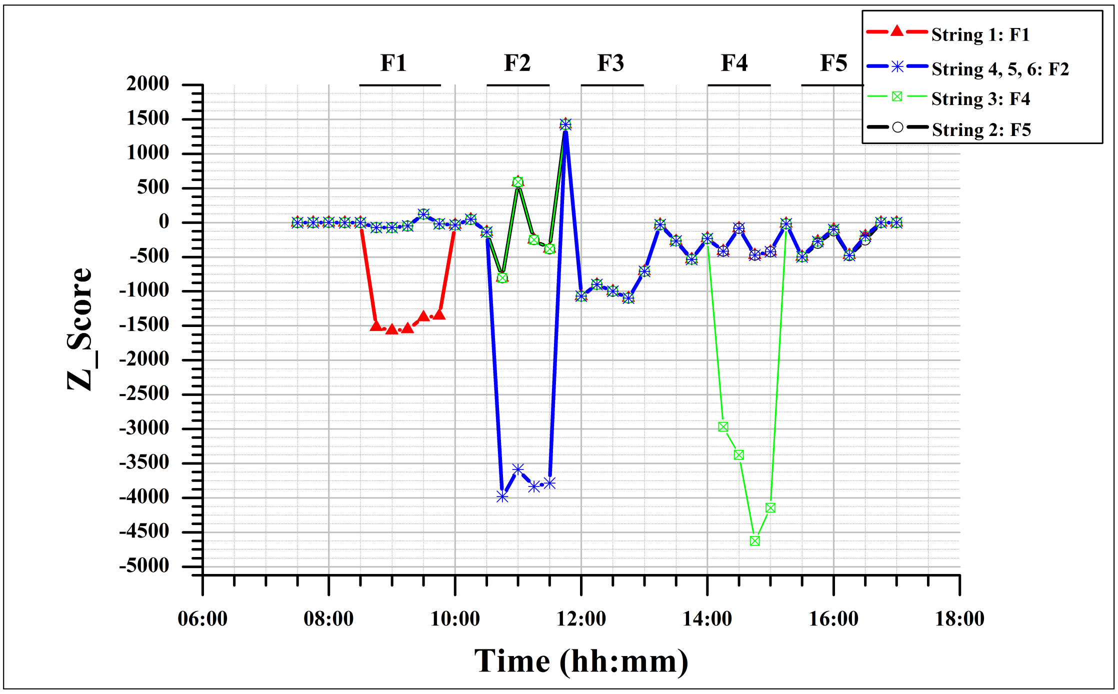


FIGURE 4.17: *Z_Score* of Strings and Their Corresponding Faults on Test Day – 2

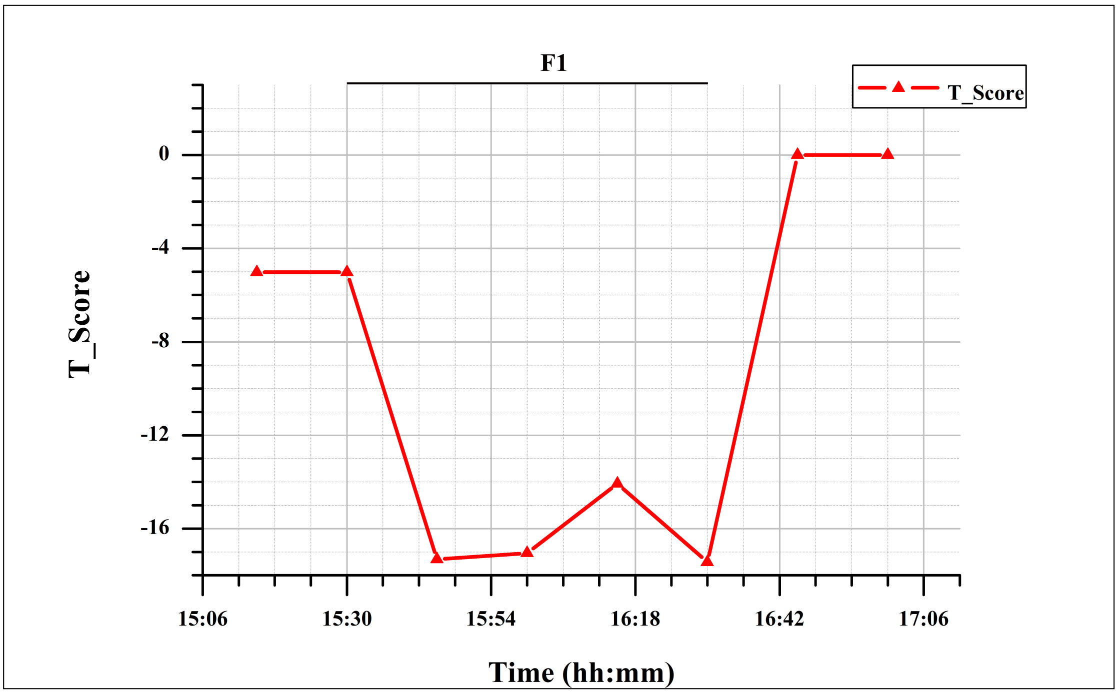


FIGURE 4.18: *T_Score* of String 2 under the Condition of Faulty PV Modules (F1) on Test Day – 2

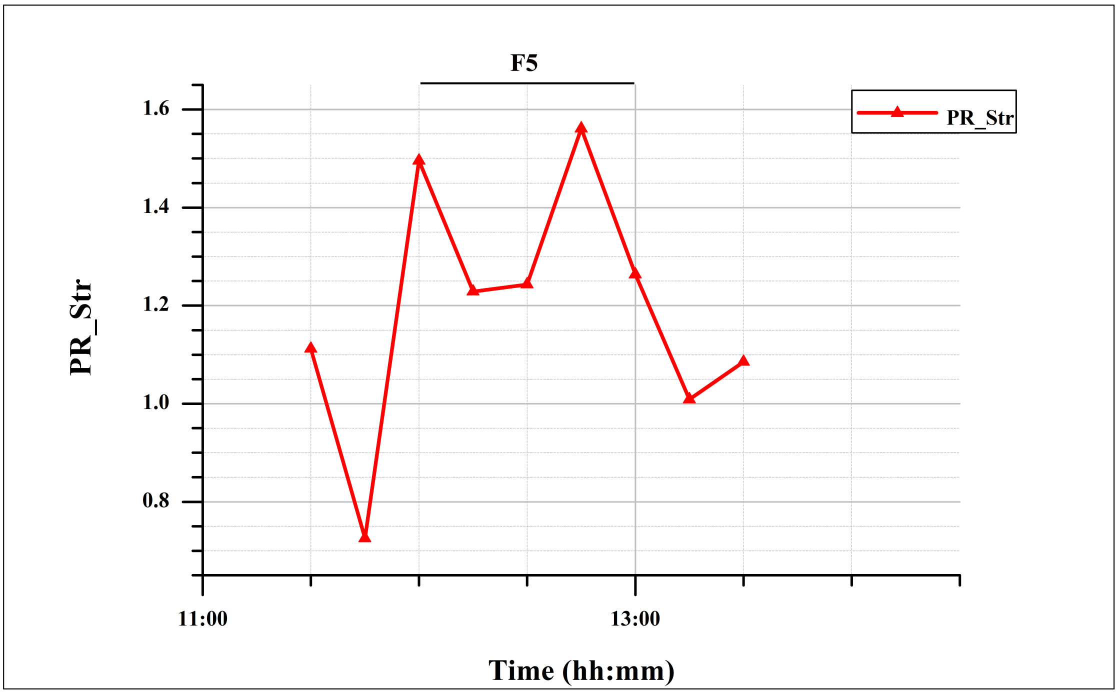


FIGURE 4.19: *PR_Str* of All Strings During Time 12:00 to 13:00 indicating MPPT Fault (F5) on Test Day – 2

The fault detection system primarily relies on the simulation of Theoretical PV Plant. For an actual scenario to implement the proposed system on a power plant, it is required that the simulation of theoretical model implemented in the MATLAB should be accurate. Minor differences can be accommodated; however, if the difference between the data from the simulated theoretical plant and physically installed PV plant is more, then the outlier detection will not be a suitable choice. This is because inaccurate modeling which will result in false alarms.

Modeling of Theoretical PV Plant is an important and critical factor while implementing this fault detection system. The modeling requires detailed knowledge and understanding of the physically operational power plant, referred as reference power plant throughout this study. The single line diagram of reference power plant, the accuracy of voltmeters and current transformers for current measurement, the precision of pyranometer and temperature sensor are all very important.

Single line diagram of the reference power plant will guide the implementer to exactly replicate the reference plant in modeling software. The type and size of PV module type and inverter are required for setting the correct parameters in the PV component. PV module characteristics such as voltage at maximum power (V_{mpp}), current at maximum power (I_{mpp}), open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) are very important to be checked from the manufacturer's datasheet. MATLAB R2018a provides the models of PV modules almost all well-known manufactures of solar modules, so this reduces the effort of the implementer in modeling the PV modules.

It is also very important for the modeling of Theoretical PV Plant that the grid voltages and frequency should be known. So the output of the inverter may be connected to proper type of grid system. Although the transformer type and other distribution network parameters are not important to be known, but the primary side voltages of transformer are required by the inverter control unit to yield a proper voltage output. Once the theoretical model is successfully modeled based on a reference power plant, the fault detection system is to be implemented based on the algorithm presented in previous chapter.

The advantages of using the proposed fault detection system are:

- It is simple and easy to implement. The only requirement for its computations is the power and voltages of all strings which can be easily obtained from PV plants.
- The fault is able to detect the DC side faults which are critical for proper functioning of a solar PV plant.
- The statistical tools that are used in the fault detection algorithm do not require cumbersome calculations. The mean and standard deviation which are very basic in statistical approaches are used.
- The fault detection system can be used with small and large scale power plants. The simple equations of Z_Score, T_Score and PR_Str can be implemented for any size of PV power plants.

It may be noted that during simulation of faults, the detection system raised an alarm of MPPT fault at proper time. The alarm disappeared and then reappeared in the set time of the fault. This glitch appeared to have occurred due to delay in data retrieval by GUI from Simulink. Although no other abnormal results of the proposed fault detection system are observed during the testing on two days data of irradiance and PV module temperature, however, there can be events when the system does not give an alarm, or may give a false alarm. Further tests may need to be performed if a false alarm or missed alarm is reported and improvements in algorithm shall be required accorded.

Further, it may also be noted that the proposed fault detection system has been developed and tested based on a 125 kWp PV power plant, it is believed that as the proposed fault detection system compares the powers of Actual PV Plant and Theoretical PV Plant at the string level where a string is a simple series combination of PV modules, so it implies that this technique should work well with any size of PV plants. Considering the limitation of an inverter to sustain a certain limit of input DC voltage, there will always be string configuration of

PV modules for any size of PV plants and therefore comparison of respective DC powers will be similar as in the experimented model. If a PV plant is large in size and it has only one string then it may be required to test if this algorithm works in such situation or not, but as of presently available models of inverters it does not seem to be to possible, also not a very good design to have one string in large-scale PV plants.

Summary

The complete thesis can be summarized such that we are living in generation when we have become almost completely dependent on technology. Our lives are reliant on gadgets, appliances and means of transportation that need too much energy. The energy consumption is multiplying every year. We are getting out of fossil fuels which are conventionally used for energy, either the electricity or fuel for transport systems. The use of conventional sources of energy such as the petroleum, coal and natural gas has resulted in the widely known term global warming. The need for alternate energy sources has brought us to use the solar, wind, tidal and biomass energy sources. These energy sources are usually referred as renewable, green or clean energy sources. Solar energy is a commonly adopted technology as the sun availability is better than the wind or tidal waves energy availability. There are two technologies in the solar energy systems, solar photovoltaic and concentrated solar thermal energy, and both have found a significant place in the field. Solar photovoltaic energy uses sunlight's photon or light energy to produce electricity.

With gradual advancement in the PV power plants technology, large scale PV power plants have been installed. There operations and maintenance requires a lot of effort due to huge number of PV modules installed on acres of land. We are still improving and there can be errors or faults that can appear during use of the machinery, same is the case with PV power plants. Usually it is considered that the PV power plants and especially the grid-connected PV power plants are unlikely to have any faults, yet it is possible to have faults with the PV modules or a complete string of a PV power plant. Also there can be faults on the power electronics circuitry which may affect the power generation. Large fields of PV arrays may also face partial shading or soiling which means to have shading or soiling on a string. These faults cause power losses and eventually reduce the performance of PV power plant.

This work has been performed to study the grid-connected PV power plants for the behavior analysis of the DC side of grid-connected PV power plants, its commonly occurring faults and development of a fault detection and identification system to indicate occurrence of an abnormality. An actually installed PV power plant has been taken as the reference power plant. MATLAB® and Simulink® are used to model and simulate the grid-tied PV power plant. Mechanism to induce faults has been implemented in the simulation design so different faults can be induced in the PV power plant at different times with the help of a GUI. An algorithm has been proposed and developed to detect faults of PV modules in a string, complete PV string failure, MPPT unit failure and partial shading and soiling loss on a PV array.

The fault detection system uses two PV power plants to simulate, one taken as an Actual PV Plant and the other as the Theoretical PV Plant. The output power of both PV plant is compared using statistical tools referred as Z_Score and T_Score in this study. The Z_Score and T_Score perform the outlier detection and indicate the faulty relevant fault based on the calculated values of these statistical parameters. Once the fault is detected and identified, the system produces an alarm that appears as an indication on the GUI.

The fault detection system is analyzed by running the simulation on different weather conditions of irradiance and temperature. The results have been formulated and it is observed that the proposed fault detection system has shown successful results and properly detected the faults.

This chapter presented the testing and evaluation of fault detection system. Advantages and limitations of proposed work are also presented. The chapter is ended with a summary of complete work conducted during the study. The next chapter presents the conclusion drawn from this study and finally the recommended future work is presented.

Chapter 5

Conclusion and Future Work

This chapter begins with the conclusions derived from the study are presented and further work recommended for future studies is mentioned at the end.

5.1 Conclusion

This study presented algorithm incorporated in a complete fault detection system that can be useful in real-time monitoring of PV power plants. The proposed fault detection system is a different approach to detect the faults in a DC side of the grid-connected PV power plant. The proposed system has gone through several tests under various conditions. The performance and accuracy of the detection system is good as no false alarms were raised during the testing.

With the help of this study, it can be concluded that a grid-connected PV power plant can have possible faults which may include but are not limited to some faulty PV modules in a string, complete PV strings not yielding any power, partial shading on PV array, soiling on PV array and a faulty maximum power point tracking unit. The power output reductions during occurrence of these faults are significant enough to put an impact on energy yields and immediate remedial actions are essential to achieve maximum output. The proposed fault detection system is a suitable addition to the available options for fault detection systems.

The advantage of the proposed fault detection system over the rest is that the proposed system has been tested on a power plant with capacity higher than 100 kW size, whereas, maximum of the fault detection algorithms as discussed in the Chapter 2 are implemented based on power plants that size below 20 kW. This makes the proposed fault detection system to have an edge of being tested on a larger system. Further this system has not given wrong indications and false alarms under the tested scenarios. This can be taken as evidence to the accuracy and precise results of this system. The implementation is simple as no other than irradiance and temperatures are required to simulate the Theoretical PV Plant in the simulation tool, secondly the current and voltages of each string are required. The proposed algorithm is implemented in MATLAB script coding making it easy for tweaking and modifying the power plant related factors such as string size, number of strings, etc as per needs.

5.2 Future Work

The fault detection system is implemented and tested on a 125 kW solar power plant. It is recommended that the proposed system be implemented on PV power plants with size of at least 1 MW to further confirm its usefulness. Also the presently proposed system is implemented and tested using simulation of both Actual and Theoretical PV plants; however, it is desired to perform this activity on a physically installed PV power plant. Voltmeters, ammeters/current transformers, pyranometer and temperature sensors for environment data may be configured to provide real-time data to the computer where computations may be performed. The actual PV plant data may be used from real life physically power plant and theoretical power plant simulated in MATLAB may be used to detect the outlier values in actual PV plant for detection and identification of faults.

The AC side faults such as anti-islanding protection, phase-mismatch, phase failure, voltage and frequency out of set ranges and voltage fluctuations are to be addressed so the fault detection system may be able to deliver at the AC side as well. Inverter efficiency and performance is also an important factor which is significant in maximum yield obtained from the PV power plant. It is also recommended that inverter efficiency factor may be incorporated in the proposed design of inverter and further examination may be performed to formulate fault identification procedures for detection and indication of inverter performance faults.

Further at the PV array side, the faults such as wiring issues, losses due to cable aging, current leakage due to weak insulation and poor connections are also possible to be examined later. The effect and potential risks associated with these faults and power output reduction during occurrence of these faults are to be studied under different conditions.

Finally a hardware product may be designed which can be used as a plug and play device for any kind of grid-tied PV power plant. This product can be beneficial for power plant operators to monitor well and for the owners PV plant to have peace of mind that their power plant is working fine and their investments are yielding fruitful financial results.

Bibliography

[1] I. E. Agency, *Key World Energy Statistics 2018*, 2018. [Online]. Available: https://www.oecd-ilibrary.org/content/publication/key_energ_stat-2018-en

[2] F. R. Pazheri, A. A. Al-Arainy, M. F. Othman, and N. H. Malik, "Global renewable electricity potential," in *2013 7th IEEE GCC Conference and Exhibition (GCC)*, Nov 2013, pp. 59–63.

[3] I. E. Agency, "2018 snapshot of global photovoltaic markets," p. 06, 04 2018.

[4] J. R. Monkowski, J. Bloem, L. J. Giling, and M. W. M. Graef, "Comparison of dopant incorporation into polycrystalline and monocrystalline silicon," *Applied Physics Letters*, vol. 35, no. 5, pp. 410–412, 1979.

[5] Y. Kolic, R. Gauthier, M. A. Garcia Perez, A. Sibai, J. C. Dupuy, P. Pinard, R. Mghaieth, and H. Maaref, "Electron powder ribbon polycrystalline silicon plates used for porous layer fabrication," *Thin Solid Films*, vol. 255, pp. 159–162, 01 1995.

[6] M. F. Nayan, S. M. S. Ullah, and S. N. Saif, "Comparative analysis of PV module efficiency for different types of silicon materials considering the effects of environmental parameters," in *2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT)*, Sep. 2016, pp. 1–6.

[7] B. Saharia, "A comparative study on converter topologies for maximum power point tracking application in photovoltaic generation," *Journal of Renewable and Sustainable Energy*, vol. 6, 10 2014.

[8] T. Solar, "Tallmax series framed 72-cell module 320-335w," 2017, original datasheet from Trina Solar. [Online]. Available: http://static.trinasolar.com/sites/default/files/Tallmax%201500V%20PE14A%20Feb2017_A.pdf

[9] M. Boxwell, *Solar Electricity Handbook*, 2017. [Online]. Available: http://www.sabz-energy.com/solar%20electricity%20handbook%202017.pdf

[10] M. A. Maehlum. Grid-tied, off-grid and hybrid solar systems - energy informative. [Online]. Available: http://energyinformative.org/grid-tied-off-grid-and-hybrid-solar-systems/

[11] E. M. Authoriy, *Handbook for Solar Photovoltaic (PV) Systems*. [Online]. Available: https://www.bca.gov.sg/publications/others/handbook_for_solar_pv_systems.pdf

[12] M. Tadj, K. Benmouiza, A. Cheknane, and S. Silvestre, "Improving the performance of PV systems by faults detection using gistel approach," *Energy Conversion and Management*, vol. 80, pp. 298–304, 04 2014.

[13] T. Takashima, J. Yamaguchi, K. Otani, T. Oozeki, K. Kato, and M. Ishida, "Experimental studies of fault location in PV module strings," *Solar Energy Materials and Solar Cells - SOLAR ENERG MATER SOLAR CELLS*, vol. 93, pp. 1079–1082, 06 2009.

[14] W. Chine, A. Mellit, A. Massi Pavan, and S. Kalogirou, "Fault detection method for grid-connected photovoltaic plants," *Renewable Energy*, vol. 66, p. 99–110, 06 2014.

[15] W. Chine, A. Mellit, V. Lughi, A. Malek, G. Sulligoi, and A. Massi Pavan, "A novel fault diagnosis technique for photovoltaic systems based on artificial neural networks," *Renewable Energy*, vol. 90, pp. 501–512, 05 2016.

[16] R. Platon, J. Martel, N. Woodruff, and T. Y. Chau, "Online fault detection in PV systems," *IEEE Transactions on Sustainable Energy*, vol. 6, pp. 1200–1207, Oct 2015.

[17] S. Silvestre, M. Aires da Silva, C. Aissa, D. Murillo, and E. Karatepe, "New procedure for fault detection in grid connected PV systems based on the evaluation of current and voltage indicators," *Energy Conversion and Management*, vol. 86, p. 241–249, 10 2014.

[18] S. Silvestre, S. Kichou, C. Aissa, G. Nofuentes, and E. Karatepe, "Analysis of current and voltage indicators in grid connected PV (photovoltaic) systems working in faulty and partial shading conditions," *Energy*, vol. 86, pp. 42–50, 05 2015.

[19] P. Jenitha and A. Immanuel Selvakumar, "Fault detection in PV systems," *Applied Solar Energy*, vol. 53, pp. 229–237, 07 2017.

[20] B. Kumar, G. Ilango, M. Jaya Bharata Reddy, and N. Chilakapati, "Online fault detection and diagnosis in photovoltaic systems using wavelet packets," *IEEE Journal of Photovoltaics*, vol. 08, pp. 257–265, 1 2018.

[21] M. Hassan Ali, A. Rabhi, A. El hajjaji, and G. Tina, "Real time fault detection in photovoltaic systems," *Energy Procedia*, vol. 111, pp. 914–923, 03 2017.

[22] M. Dhimish, V. Holmes, B. Mehrdadi, M. Dales, and P. Mather, "Detecting defective bypass diodes in photovoltaic modules using mamdani fuzzy logic system," *Journal of Electrical and Electronics Engineering*, vol. 17, pp. 33–44, 12 2017.

[23] M. Dhimish and V. Holmes, "Fault detection algorithm for grid-connected photovoltaic plants," *Solar Energy*, vol. 137, p. 236–245, 11 2016.

[24] M. Dhimish, V. Holmes, and M. Dales, "Parallel fault detection algorithm for grid-connected photovoltaic plants," *Renewable Energy*, vol. 113, pp. 94–111, 12 2017.

[25] M. Dhimish, V. Holmes, M. Dales, P. Mather, M. Sibley, B. Chong, and L. Zhang, "Fault detection algorithm for multiple GCPV array configurations," in *2017 IEEE Manchester PowerTech*, 06 2017, pp. 1–6.

[26] M. Dhimish, V. Holmes, B. Mehrdadi, and M. Dales, "Simultaneous fault detection algorithm for grid-connected photovoltaic plants," *IET Renewable Power Generation*, vol. 11, no. 12, pp. 1565–1575, 08 2017.

[27] M. H. Rashid, "Power electronics: Circuits, devices, and applications," pp. 237–246, 2009.

[28] T. Erfidan, S. Ürgün, and B. Hekimoğlu, "Low cost microcontroller based implementation of modulation techniques for three-phase inverter applications," in *MELECON 2008 - The 14th IEEE Mediterranean Electrotechnical Conference*, 05 2008, pp. 541 – 546.

[29] S. Seo, "A review and comparison of methods for detecting outliers in univariate data sets," *University of Pittsburgh*, pp. 9–17, 01 2006.

[30] H. A. David and J. L. Gunnink, "The paired t-test under artificial pairing," *American Statistician - AMER STATIST*, vol. 51, pp. 9–12, 02 1997.

[31] R. A. Fisher, "Applications of Student's distribution," *Metron*, vol. 5, pp. 90–104, 1925.