Yarmouk University
Hijjawi Faculty for Engineering Technology

Stability Analysis for Photovoltaic Connected Distribution Grid

A Thesis Submitted to
The Department of Electrical Power Engineering

In partial fulfillment
of the requirements for the degree of
Master of Science

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My gratitude goes to my mother, family members, and friends for their love, moral support and understanding and support.

Khaled al-za'areer

DECLERATION

I am, khaled alza'areer, recognize what plagiarism is and I hereby declare that this thesis proposal, which is submitted to the department of Electrical Power Engineering at Hijjawi Faculty for Engineering Technology, for the partial fulfillment of the requirements for the degree of Master of Science, is my own work. I have not plagiarized from any sources. All references and acknowledgments of sources are given and cited in my proposal. I have used the conventional citation and referencing. Each significant contribution to and quotation in this report from work of other people has been attributed and referenced.

Khaled alza'areer

DEDICATION

I dedicate this work to my parents, my friends, and anyone helped me to complete this thesis.

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LIST OF SYMBOLS

PV	Photovoltaic
I	Output Current of the PV Cell
I_{ph}	Current Generated by the Incident Light
I_d	Shockley Diode Current
I_{sh}	Current Passed through Shunt Resistance of Diode
I_o	Reverse Saturation Current of Diode
q	Electron Charge (1.602×10^{-19} C)
V	Output Voltage of the PV Cell
k	Boltzmann's Constant (1.381×10^{-23} J/K),
T_c	Junction Temperature in Kelvin
a	Ideality Factor
R_S	Series Resistance of Diode
R_{Sh}	Shunt Resistance of Diode
N_P	Number of Cells Connected in Parallel
N_S	Number of Cells Connected in Series
I_{sc}	Short Circuit Current
V_{oc}	Open Circuit Voltage
V_t	The Thermal Voltage
MPP	Maximum Power Point
P_{max}	Maximum Power Delivered to The Load
A	Cell Area
G	Ambient Radiation
K_I	Cell's Short-Circuit Current Temperature Coefficient,
T_{ref}	Cell's Reference Temperature,
G	Irradiation on the Device Service (in W/m^2),
I_{RS}	Cell's Reverse Saturation Current at a Reference Temperature and a Solar Radiation,

E_g	Bang-Gap Energy of the Semiconductor Used in the Cell
STC	Standard Test Conditions
P_l	Real Power Losses
P_{Gi} , Q_{Gi}	The Injection Powers of PV Generators to the Bus
P_{Di} , Q_{Di}	The Load Demand
P_i , Q_i	The Active and Reactive Power of the Buses.
α_i	Sensitivity Factor

ABSTRACT

Distributed renewable energy has generated significant interest over the last few years with the increasing concern about the global environmental protection to produce pollution free natural energy. Jordan became one of the countries which looking for interesting in distributed renewable generation interfaced to power distribution system. Renewable energy sources such as solar, wind, and biomass have shown great potential for viable usage in distributed generation systems in compared to production from fossil fuels. As an alternative source of energy for the future, solar energy is clean, pollution free and inexhaustible. Solar energy is among the fastest growing energy sources in the world.

The primary market of solar energy was in off-grid photovoltaic (PV) applications. Nowadays, the global market is for grid-connected applications where the power is fed into the electrical network. Grid-connected distributed PV covers a wide range of power levels ranging from single phase systems to large three-phase systems. Recent studies show an increase in the worldwide installed photovoltaic power capacity. Lately, the tendency to apply large scale of PV is increasing.

Large scale PV can affect the stability and operation of utility grid. The concern of this work is the impact of PV systems on the behavior of the distribution system. Simulations and analysis were implemented on Irbid District Electrical Company (IDECO) grid in this study. The PV systems are interfaced to the grid by a power electronic inverter. In this study, CYME power flow software and MATLAB are used to investigate these results. The impact of distributed PV system on the power flow and voltage profile of a distribution system has been analyzed while connected to IDECO grid. The impact of different PV generation penetrations on the power flow and voltage profile are compared. Moreover, the impact of the location where PV is installed is investigated. Various test scenarios corresponding to different weather conditions such as solar radiation and temperature are simulated. Sizing and allocation of the PV system in the tested feeder are optimized.

Keywords: Photovoltaic, Stability, CYME

CHAPTER ONE

INTRODUCTION

Ch.1 INTRODUCTION

1.1 ***Introduction to Power System Stability***

1.1.1 ***Stability Definition***

Power system Stability can be defined as ability of the system to remain in a state of operating equilibrium at normal operation conditions, and to restore its normal state after being subjected to abnormal conditions [1]. Stability problems are generally divided into two major categories, steady state stability and transient stability [2]:

1. *Steady state stability*: means ability of the system to maintain synchronism when subjected to small disturbances, such as gradual power changes.

2. *Transient stability*: means ability of the system to maintain synchronism when subjected to large disturbances, such as occurrence of a fault, sudden outage of unit or line, and sudden application or removal of large loads.

1.1.2 ***Stability Classifications***

Power system stability is divided into three parts [1], [2]:

1. *Rotor angle stability*: means ability of interconnected generators to maintain in a synchronism. Rotor angle stability can be small signal stability or transient stability according to disturbance subjected to power system.

2. *Frequency stability*: means ability of the system to maintain steady frequency in the system after being subjected to a disturbance following a severe upset resulting in a

significant imbalance between generation and load. Frequency stability can be a short term phenomenon or long term phenomenon.

3. *Voltage stability*: means ability of the system to maintain steady voltages at all buses in the system after being subjected to a disturbance. Voltage stability can be divided into Small disturbances voltage stability and large disturbances voltage stability.

1.1.3 Voltage Stability

Voltage stability depends on the ability to maintain equilibrium between load demand and load supply from the power system. It can be divided into small disturbances voltage stability and large disturbances voltage stability. Large disturbance voltage stability refers to the system ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. Small-disturbance voltage stability refers to the system ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load [2].

Voltage instability has been given much attention by power system researchers in recent years. Voltage instability is a phenomenon in which the receiving end voltage decreases well below its normal value and does not restore its condition, or continues to oscillate against the disturbances. The power system experiences voltage instability when there is a real and/or reactive power imbalance between the generators and the loads. Voltage collapse is the process by which the voltage falls to an unacceptable value leading to a blackout or abnormally low voltages in the power system [3].

Once associated with in the weak systems and long lines, voltage problems are strongly appeared [3]. The voltage stability behavior of the power system changes significantly when distributed resources are added to the grid as a result of the reconfiguration of the power flow. Therefore, it is necessary to properly model and analyze the impact of adding distributed generators in the grid.

1.2 Distributed Renewable Energy

The electricity generation can be divided into fossil fuels and nuclear and renewable generation. Fossil fuels and nuclear energy are finite sources of energy that cannot be sustained in the long term. This conventional energy significantly pollutes the atmosphere and can be quite harmful to the environment through the burning of oil in the process of conversion to electricity. The combustion process produces significant amount of carbon dioxide (CO_2), methane (CH_4) and other greenhouse gases causing global warming. In addition to environment impact, a global economic problem was presented due to a rapid increase in the price of oil and fossil fuels which are the primary sources of energy around the world. The growth in demand could be met by increasing the power generation. When generating stations are located far away from the loads, power has to be transmitted over long distances and there are significant amounts of power losses. In recent years, transmission capacity is inadequate and limitation in constructing new transmission lines is apparent. These reasons are the main driving forces behind the concept of distributed renewable energy [4], [5].

The power produced from renewable energy resources will lead to a significant reduction in rate of environmental pollution in comparison with the production by traditional energy. The use of renewable and alternative energy sources can save money, and free us from the uncertainties of depending on energy supplied from the outside of Jordan. Distributed renewable energy adds additional generation to meet future global energy requirements due to population and industrial growth. Distributed generation consists of different sizes generators cited close to the customer to supply electrical power needed by customers. By locating close to consumers, distributed generation provides advantages in efficiency and flexibility over a large scale because of short construction lead times compared to most types of power plants, size and expandability. The alternative sources of energy will become the primary source of energy to meet global demand [4], [5].

Over the past few decades there has been a lot of interest in alternative sources of energy and several approaches have been suggested. Nowadays, the renewable energy production is very modest compared to the traditional energy production as fossil fuels. The renewable electricity generation could be divided depending on the energy source which is used in: solar energy, hydropower, wind power, and biomass energy [6]. As the renewable energy continues in the expansion, concerns about its impact on the stability and operation of the grid have grown. Renewable energy can play a significant role in improving grid performance, voltage stability and the quality of the power.

Solar photovoltaic systems are the fastest growing energy sources in the world. Solar energy is friendly and cost efficient alternatives to fossil fuels [6].

1.3 Solar Energy Systems

One technology to generate electricity is to use solar cells to convert the sunlight into electricity. Photovoltaic (PV) systems are the most famous solar system in the world. Figure 1.1 shows PV arrays. Solar energy is the world's major renewable energy source and is available everywhere in different levels of irradiation. The amount of sunlight received by solar systems depends on several factors such as geographical location, time of the day, season, and local weather. Solar energy has several advantages such as availability of sun energy during peak time, long life cycle, and short lead time to design. Utilizing of solar energy systems are a Static structure with no moving parts, hence quiet operation, and simple maintenance is needed. Another advantage is that solar technology can be easily scaled to provide the required power for different loads [7], [8]. Disadvantages of solar energy utilizing are the initial costs of the equipment, large area is required for system installation and clouds can reduce the energy of the sunlight.

Currently, solar energy systems are actively being used in order to mitigate environmental issues such as the greenhouse effect and air pollution [9]. Electricity available at the terminals of solar array can directly feed small loads or connected to the grid. Grid connected solar systems make its energy available for use by other customers and reduce the amount of energy that has to be generated by conventional generators.

Figure1.1: PV arrays

Some solar energy applications require electronic converters to process the electricity from the photovoltaic device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems and to track the maximum power point (MPP) of the device [10].

Grid connected solar energy generation represents an alternative renewable energy that is becoming more popular due to the new favorable governmental laws and policies.

1.4 Impacts of PV Energy on Power System

The emphasis on effects of large scale PV generators connected to distribution system on its grid has been increased in the past years. Large scale PV generators connecting to grid will have consequences not only on the distribution networks but also on the transmission system. These

Impacts are mainly related to the installation location and scale of PV system. The main impacts of large scale solar PV generations on power grid are: electricity quality, protection relay, voltage and frequency stability, and electricity market [6], [11].

When the PV output power quantity is large enough, voltage pulsation on transmission and distribution lines will appear. PV systems also produce harmonics to network since they are connected to grid through power electronic converters.

Solar PV units are normally equipped with protection schemes designed to disconnect it from the network when needed, the normal operation of protection relay might be influenced. If solar PV systems cannot coordinate with the original system relays installed at distribution system, the relays where PV systems connected will have a possibility to trip incorrect.

In addition, the market of distribution system side in some countries is still not opened up to now, but the connection of PV generations to power grid is closely related to the electricity market of distribution side.

Grid-connected photovoltaic has some impacts on system stability in both distribution and transmission networks. If PV systems capacity is large enough, frequency problems may also occur at power grid. Grid frequency might fluctuate from time to time.

Impacts of PV on Voltage Stability: The power system voltage stability is affected by the ability of generating sources to supply sufficient real and reactive power to the loads. The voltage stability behavior of the power system changes significantly when solar PV arrays are added to the grid as a result of the reconfiguration of the power flow. Therefore, it is necessary to analyze the impact of adding such systems to the grid [11].

As the total capacity of PV generation increases, it will have some side effects on the voltages of distribution system, it may have some influences on the voltage of high voltage level power grid, and it may cause voltage stability problem especially at those loads when large amount of PV systems are applied [11].

When PV generators are added to system grid, the power flow of the system could be changed due to an additional injected power into the system, injected power could cause a variation in the voltage profile of the system nodes, and the power flow in the lines may become different. This problem will be investigated in this work.

1.5 Power Flow Analysis

Power flow study is an important for power system analysis. It analyzes the power systems in normal steady state operation under various operating conditions. The power flow analysis is used for a power system to find the voltage magnitude and phase angle at each bus, the power flow through each line, and the power production at each generator.

Power flow study usually uses one-line diagram, and per-unit system for analyzing. The power flow begins with identifying the variables in the system. The variables are dependent on the type of bus. There are three types of buses:

1. Load Bus: a bus without any generators connected to it. It is assumed that the real power and reactive power are known, so it is also known as PQ bus.

2. Generator Bus: a bus with at least one generator connected to it. It is assumed that the real power generated and the voltage magnitude is known, so it is also known as PV bus.

3. Slack bus: a Bus having a generator arbitrarily selected. It is assumed that the voltage magnitude and voltage phase are known.

For each load bus, both the voltage magnitude and angle are unknown. The voltage angle is unknown for each generator bus. There are no variables that need to be solved for the slack bus.

1.6 Problem Overview

Because Jordan is not oil and fossil energy producing country, it spends large amount of money to produce electricity by conventional plants. So, the research on an alternative energy is needed especially with the continuous increase of power demand.

Jordan receives a high average of solar radiation. According to data collected from National Center for Research and Development\Energy Research Program (NECR), the Average Daily Horizontal Solar Radiation incident on one square meter area in KWh/m^2.day for Jordan/Amman for the year 2010 is explained in Figure 1.2. So, it is very efficient to implement the solar energy in Jordan.

The study will concern on the impact of grid connected PV on power flow and voltage profile. The impact of different penetrations and locations of PV system, and solar radiation and temperature variations on power flow and voltage profile will be discussed.

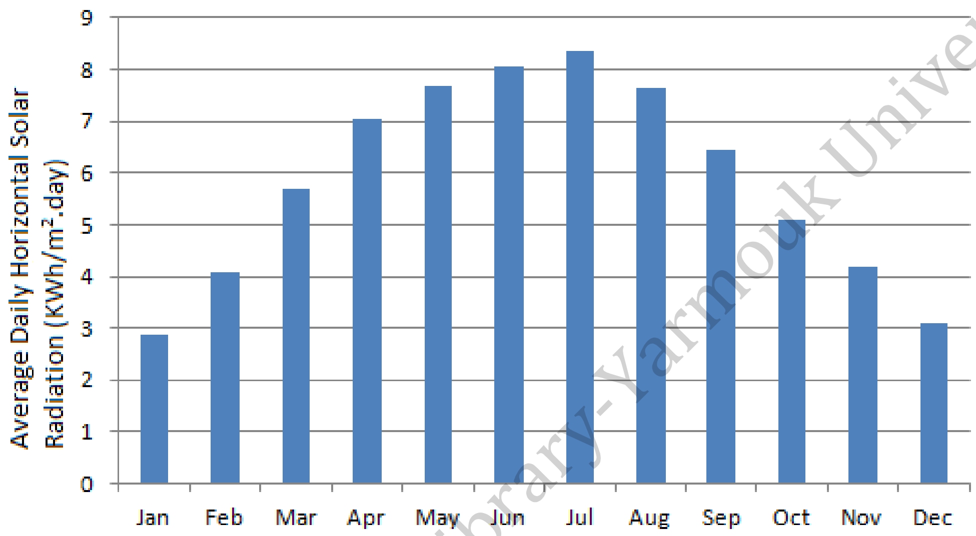


Figure 1.2: Average daily horizontal solar radiation incident on one square meter area

1.7 Thesis Organization

The thesis consists of six chapters. An introduction to power system stability, and advantages of distributed renewable energy especially solar energy was presented in ***chapter one***.

Chapter 2 will include a literature review on the photovoltaic systems model, the PV behavior and characteristics, and photovoltaic impacts on system especially voltage stability. The objectives for conducting this thesis also are discussed in this chapter.

Chapter 3 describes the photovoltaic performances and defines a suitable model for a PV array. The response of a PV system to changes in solar radiation and temperature will be explained.

Chapter 4 describes the system configuration which will be studied including the parameters and loads, and solar PV module parameters. Software programs used in this thesis will be explained in this chapter.

Chapter 5 shows results of the study case simulations. Two topics results will be explained, power losses, and voltage profile. Analysis for these results will be presented. This chapter will also include analytical method to achieve optimum size and location for PV system.

In ***chapter 6***, conclusions of this thesis will be summarizing, recommendations and future topics will be suggested.

The ***References*** will be attached at the end of the thesis.

CHAPTER TWO

LITERATURE REVIEW

Ch.2 LITERATURE REVIEW

2.1 *Introduction*

From the literature, it is found that most of the contributions show that grid connected PV system has valuable impacts on power system operating conditions especially power flow and voltage profile.

In [11] the impacts of PV generation on power system are discussed, including: electricity quality, power flow control, and voltage and frequency stability. The technical challenges and possible solutions when large amounts of PV systems are connected to high voltage level power grid are both presented.

In order to estimate the electrical behavior of the cell with respect to changes on environmental parameter of temperature and solar radiation, a simulation model for a PV cell is defined in [12]. An accurate PV module electrical model is presented based on the Shockley diode equation .The general model was implemented on Matlab file, and accepts irradiance and temperature as variable parameters and outputs the I-V characteristic. A particular 60 Watt solar module was used for model evaluation and results was compare with points taken directly from the manufacturer's curves and show excellent correspondence to the model. The model development was used to show the effect of: irradiation, temperature, and ideality factor and series resistances. This paper is also aims to develop a complete solar photovoltaic power electronic conversion system in simulation, and a general model to simulate the electrical behavior of the PV systems in a grid connected application.

In [13] a photovoltaic array simulation model to be used in Matlab/Simulink GUI environment is developed and presented. The model is developed using basic circuit equations of the photovoltaic (PV) solar cells including the effects of solar irradiation and temperature changes. The model was tested using a directly coupled dc load as well as ac load via an inverter. The model is simulated connecting a three phase inverter showing that, the generated dc voltage can be converted to ac and interfaced to ac loads as well as ac utility grid system.

A method of modeling and simulation of PV arrays is proposed in [14]. The main objective is to find the parameters of the nonlinear I–V equation by adjusting the curve at three points: open circuit, maximum power, and short circuit. With the parameters of the adjusted I–V equation, one can build a PV circuit model with any simulator by using basic math blocks.

In [15] a model of PV generation suitable for studying its interactions with the power system was described. A significant increase in the capacity of PV generation could have a significant impact on the stability of the transmission network. Experimental results suggest that the maximum power point tracking of the PV generator plays a critical role in the dynamic response of the PV system. These experimental results are used to develop a PV model. The proposed model is capable of representing the system's response to changes in irradiance.

In order to achieve parallel operation of two, three, and four units of PV systems, 250kW grid-connected inverters are evaluated in [16] reaching a total capacity of 1MW when four units are operating. The concept is to treat these four parallel connected units as one equipment, being able to operate jointly or separately as required. Test results for the parallel connection of grid-connected inverters for one MW photovoltaic system are presented. Results show the feasibility of the parallel connection keeping the same characteristics as a single unit.

In [17] a 100 kW grid connected PV system is simulated. A full three phase current controlled pulse width modulator (PWM) bridge inverter with a passive LCL filter is used for interfacing with the utility and named as power conditioning unit (CU). The main functions of CU are maximum power point tracking control (MPPT) and power factor correction. The MPPT algorithm, the LCL filter and controller's designs are discussed. Simulation results show the validity of that PV system under various weather conditions.

The design and the simulation of a 10 kW PV system in areas of high solar radiation are investigated in [18]. The importance of this study is to explore the feasibility of connecting the PV system with a grid to generate electricity at campus of Hashemite University in Jordan whose yearly global irradiation is 2000 kWh/m^2. The METEONORM and the PV SOL simulation software were used. This study calculates the cost of one kWh generated by the PV system and then compares it with the public electricity tariff. The study also presents a comparison between the performances of different PV panel sizes with different inclination angles.

In [19] the effect on distribution network power flow, voltage, and relay protection with penetration of photovoltaic system is studied. To study the effect to distribution network's power flow, the bus voltages are calculated when the power factor of the photovoltaic power varies from -0.95 to +0.95 and photovoltaic power varies from 0MW to 1.5MW. To study the effect to distribution network's voltage, the voltage of the node connecting PV power with grid is adjusted by adjusting photovoltaic power factor. The effect of photovoltaic power on relay protection in distribution network is studied. This thesis shows that the effects of photovoltaic power on short-circuit current and relay protection are different when the location and the capacity of photovoltaic power are different.

A mathematical model suitable for stability analysis that includes the nonlinear behavior of grid connected photovoltaic modules was presented in [20]. Using this model, it was shown there two solutions for a specific power injection into the grid mains one of which is unstable. Eigenvalue analysis was introduced to define regions of attraction that determine the dynamics of the converter states. Simulations were done to support the mathematical analysis. Results showed that the system is near to instability under high loading levels.

In [21] the analyses of impact of grid connected photovoltaic system on the voltage response at the point of common coupling (PCC) of power system were presented. The models of 3-bus power network, photovoltaic panel and photovoltaic inverter are proposed. This paper presents analyses on the static and transient voltage characteristics. Also, it studied the influences on PV response at different variations of temperature, solar radiation. The static voltage response, known as a PV curve, for the photovoltaic system is analyzed. The voltage transient behaviors caused by the variation of parameters in photovoltaic generation system are also studied. In this paper, the impact of system parameters on stability can be measured using stability sensitivity analysis.

In [22] grid connected PV model as three phase source for three phase distribution load flow was presented and their effect when they are connected in distribution network was analyzed. In this paper, the PV was modeled as PQ node with Q limit and as PQ node with have five different type of P calculation. The three phase load flow program with Photovoltaic models has been tested using IEEE 13 node feeder. The analysis is carried out with various photovoltaic mathematical models. The simulation results show that the integration of grid connected PV into a distribution network can improve the voltage profile and reduce the total system losses.

The impact of large solar plants on power systems due to rapid variation in power injection caused by variations in the solar radiation, changes in temperature and disconnecting of power converters connected to the system was presented in [23]. The Maximum Power Point Tracking (MPPT) algorithm and a mathematical model of Photovoltaic array based solar plant were incorporated using PSS/E software. The model produces changes in DC power output for changes in its two inputs solar irradiance and temperature. The PV plants are added to the 39-bus New England test system at three different locations. The power generation from PV has been increased up to 20% and was randomly distributed between three plants. The dynamic behavior of the system was studied by changing the solar radiance, disconnecting of the PV plant and by applying a three phase fault at PV connected bus. It was found that with large PV plant, the system is stronger to stability problems.

In [24] a novel approach based on eigenvalue approach and nonlinear model simulations to investigate both transient and steady state performance of a photovoltaic array connected to a large utility grid is presented. The dynamic equations of the studied PV utility system are derived to examine the dynamic characteristics of the studied system under different operating conditions. The transient responses of the studied PV under different operating conditions are also examined. It can be concluded from the results that the proposed methods are effective to explore the transient performance and dynamic characteristics of the studied system under different disturbance conditions.

Fault condition analysis in a grid connected Photovoltaic energy system is explained in [25]. The grid connected PV energy system is operated under different level of solar radiation. The output current of the Voltage Source Inverter at different level of solar radiation are analyzed. The result shows the impact of various solar radiations on the system stability and the need for good control system. The grid connect PV energy system was simulated using Matlab/Simulink.

The next generation of power energy systems using solar and wind energy systems for the country of Jordan is presented in [26]. Sights are chosen to produce electricity using the wind in the Mountains in Northern Jordan and the sun in the Eastern Desert. The opportunity of a large wind and solar hybrid power production is being explored. This paper also looks at some of the modern power electronics converters which have improved significantly solar and wind energy technologies.

To analyze impacts of the grid connected large scale photovoltaic (LSPV) power station on voltage profile along the transmission line to the local power grid is presented in [27]. Several conclusions can be drawn from analyses of the voltage profile: The voltage of each bus is a nonlinear function of the LSPV real power output, and the V-P curve shows parabolic trends, with a maximum voltage point existing on it.

In [28] a large scale photovoltaic system installed in a Main Stadium has been investigated for study the impact on power losses of the study feeder. The PV power generation is simulated according to the hourly solar radiation and temperature. Also, the impact of voltage variation and power loss of the distribution feeder by the PV generation system has also been performed by 3-ϕ load flow analysis. It is found that the voltage drop of 0.51% can be mitigated and the daily power loss reduction of 96.4 kWh has been obtained for the distribution feeder after the installation of the PV system.

The model in [29] can simulate steady state operation of PV systems in condition of giving meteorological, PV system and power grid parameters. From the simulations using power flow equations, it is found that the variations of meteorological and power grid parameters will affect the system operation, but the irradiance is the greater one. The power flow analysis is verified on IEEE 30-bus system.

In [30] the impact of large scale photovoltaic generation system on power system voltage stability is examined. A model of large scale PV generation system in IEEE-14 bus test system has been used for investigate the results. Based on simulation results, it appears that PV location, sizes and the way they are integrated as concentrated or scattered have different impact on voltage stability of the system.

The modeling and analysis of the characteristic and the interactions with grid for large scale grid connected photovoltaic systems are presented in [31]. For a MW level PV system, numbers of inverters with relatively smaller capacity are employed to operate in parallel. This paper proposed and verified a novel method toward max power point tracking MPPT of large area PV arrays. Results show that the fluctuation depends mostly on the degree of solar radiation fluctuation, capacity of the PV plant.

Fault current contribution from large scale photovoltaic system and protection issues are discussed in [32]. The mentioned problems were investigated in PSCAD model of 50 MW of grid connected PV system where various operating condition of the network and penetration levels of PV were considered. The dynamic model of a PV generation system interconnected to radial distribution network is presented. Large number of simulation cases for large scale PV power plant fault contribution is presented.

In [33] simulations studies have been carried out to investigate the impact of a large penetration of PV generation on the power system. The dynamic response of a PV generation system to rapid changes in solar radiation is analyzed. Simulation results show that for the PV systems that are not equipped with a voltage controller, the connected bus voltage fluctuates during periods of large change in solar radiation. Two forms of voltage control techniques used to mitigate the negative effects of rapid changes in irradiation are investigated using simulation. The dynamic response of PV generation when subjected to faults is also analyzed.

The impact of large scale PV generation on Bangladesh power system stability is investigated in [34]. The system loading margin is studied without and with PV generation system. The influence of solar radiation and penetration of PV system on system is considered for the system study. This paper shows that the interconnection of PV generation system to the Bangladesh power system will make the system strong against voltage instability problem.

2.2 Thesis Objectives

This thesis investigates impact of PV generation of grid connected PV on behavior of power distribution systems.

The first objective is to enhancement the relationship between the industrial and the academic schemes in Jordan. This study deals with real life grid (Irbid District Electrical Company).

The second objective is to connect the PV system model into a distribution power system to investigate the behavior at overall system.

The third objective is to study impact of PV generation system on power losses and voltage stability of distribution grid, and to compare impact of different penetrations of photovoltaic generation.

The fourth objective is to study impact of different locations of PV system on power losses and voltage stability of distribution grid.

The fifth objective is to study impact of variations of solar radiation and panel temperature on power losses and voltage stability of distribution grid.

The sixth objective is to achieve the optimum size and location for PV system that could installed into Ajloun feeder to get the minimum losses and best voltage profile.

CHAPTER THREE

PHOTOVOLTAIC PERFORMANCE

Ch.3 PHOTOVOLTAIC PERFORMANCE

3.1 Introduction

Photovoltaic (PV) literally means light-electricity. The term “Photo” means produced by light, and the “Voltaic” means electricity produced by a chemical reaction [35]. Solar PV systems convert light energy into electricity by the interaction of sunlight with certain semiconductor materials, such as silicon. The electrons are collected to form a direct current (DC) of electricity. Many cells may be connected together to produce a PV module, and many modules are linked together to form a PV array.

A typical photovoltaic cell consists of semiconductor material has a p-n junction similar to a diode that directly converts solar radiation into DC current using the photovoltaic effect as shown in Figure 3.1. Many semiconductor materials are suitable to create solar cells. The most commonly used material is silicon (Si) which is specially treated to form an electric field, positive on one side and negative on the other towards the sun. Silicon PV cells are composed of a thin layer of bulk Si connected to electric terminals [36]. If electrical conductors are attached to the positive and negative sides, the electrons are captured in the form of electric current.

When solar photons hit the solar cell, with energy greater than band gap energy of the semiconductor, the energy level of electrons raises and frees them from their atoms. The electric field at the p-n junction pushes the electrons into the n region while positive charges are driven to the p region creating a current can flow on other cells or to the load. The current generated in the solar cell is proportional to the solar radiation. Solar radiation absorbed by the semi-conductor material is the radiant power incident per unit area upon a surface expressed in W/m^2 [12], [38].

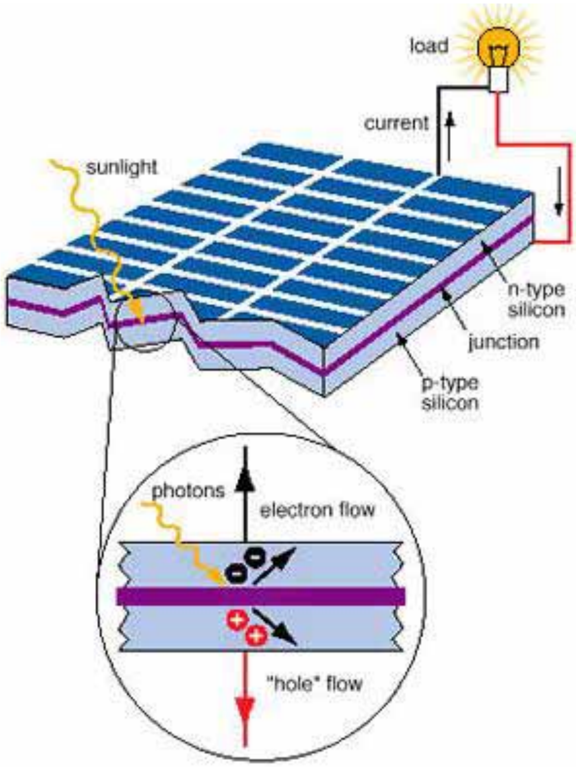


Figure 3.1: Typical thin-film amorphous silicon construction [37]

Other external factors such as the ambient weather conditions like temperature, illumination, and shading, also affect the solar PV array output. The solar PV cell is able to generate the maximum power at a specific operating point, but that operating point varies depending on the ambient weather conditions, this varying makes it difficult to predict the expected output power at a given time for that location.

3.2 Photovoltaic Cell Modeling

The basic device of a photovoltaic system is the solar cell [10]. During darkness, the solar cell is not an active device; it works as a diode [12]; it produces neither a current nor a voltage. The photocurrent generated when the sunlight hits the solar panels can be represented with a current source and the p-n junction of the solar cell can be represented with a diode. The equivalent circuit of solar cell is shown in Figure 3.2.

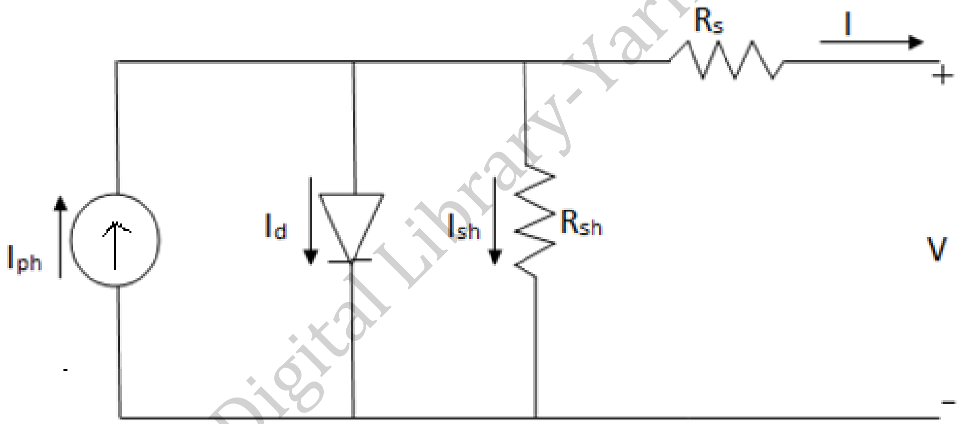


Figure 3.2: Equivalent circuit of solar cell

The mathematical model of the current-voltage characteristics of solar cells is a nonlinear equation that is very difficult to solve. The solar cell is usually represented by the single exponential model. The model contains a current source I_{ph}, one diode, a series resistance R_S representing the voltage losses inside each cell and in the connection between the cells, and shunt resistance R_{Sh} representing the leakage currents occur throughout the cell [10], [39].

The voltage and current relationship of the solar cell is derived from Kirchhoff's current law [7], [31], [40]. According to Kirchhoff's current law, the net current is

$$I = I_{ph} - I_d - I_{sh} \tag{3.1}$$

$$I_d = I_o \left(e^{\frac{q(V+I\,R_S)}{akT_C}} - 1 \right) \tag{3.2}$$

$$I_{sh} = (\frac{V+IR_S}{R_{Sh}}) \tag{3.3}$$

As a result:

$$I = I_{ph} - I_o \left(e^{\frac{q(V+I\,R_S)}{akT_C}} - 1 \right) - (\frac{V+IR_S}{R_{Sh}}) \tag{3.4}$$

Where:

I Output Current of the PV Cell (A),

I_{ph} Current Generated by the Incident Light (A),

I_d Shockley Diode Current (A),

I_{sh} Current Passed through Shunt Resistance of Diode (A),

I_o Reverse Saturation Current of Diode (A),

q Electron Charge (1.602×10^{-19} C),

V Output Voltage of the PV Cell (V),

k Boltzmann's Constant (1.381×10^{-23} J/K),

T_c Junction Temperature in Kelvin (K),

a Ideality Factor (Typically between 1-2),

R_S Series Resistance of Diode (Ω),

R_{Sh} Shunt Resistance of Diode (Ω).

Recently, a lot of researchers have developed models that neglect the shunt resistance R_{Sh} since the shunt resistance is normally very large. The value of Rs is very low and sometimes this parameter is neglected too [10].

3.3 Photovoltaic Array

Multiple solar cells required to be connected in series or in parallel to produce enough voltage and power are called module or panel. PV modules can be grouped to form array mounted on the same plane to provide enough electrical power for a given application as shown in Figure 3.3.

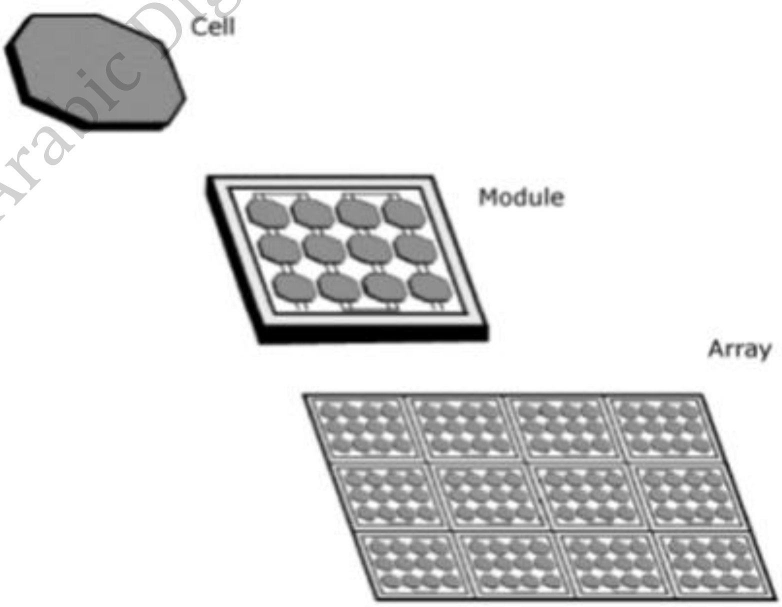


Figure 3.3: Photovoltaic cell, module, and array

Cells connected in parallel increase the output current and cells connected in series increase the output voltage [10], [35]. An equivalent circuit of array composed of N_P parallel and N_s series connections of cells is shown in Figure 3.4. The photovoltaic current, saturation current, series resistance, and the shunt resistance can be expressed as [10], [41]:

$$I_{ph,array} = N_P \, I_{ph,cell} \qquad 3.5$$

$$I_{o,array} = N_P \, I_{o,cell} \qquad 3.6$$

$$R_{S,array} = \frac{N_s}{N_P} R_{S,cell} \qquad 3.7$$

$$R_{Sh,array} = \frac{N_s}{N_P} R_{Sh,cell} \qquad 3.8$$

So, the output current of the photovoltaic array will be become [7], [41]:

$$I = N_P I_{ph} - N_P I_o \left(e^{\frac{q(V/N_S + I\,R_S/N_P)}{akT_C}} - 1 \right) - \left(\frac{N_P V/N_S + IR_S}{R_{Sh}}\right) \qquad 3.9$$

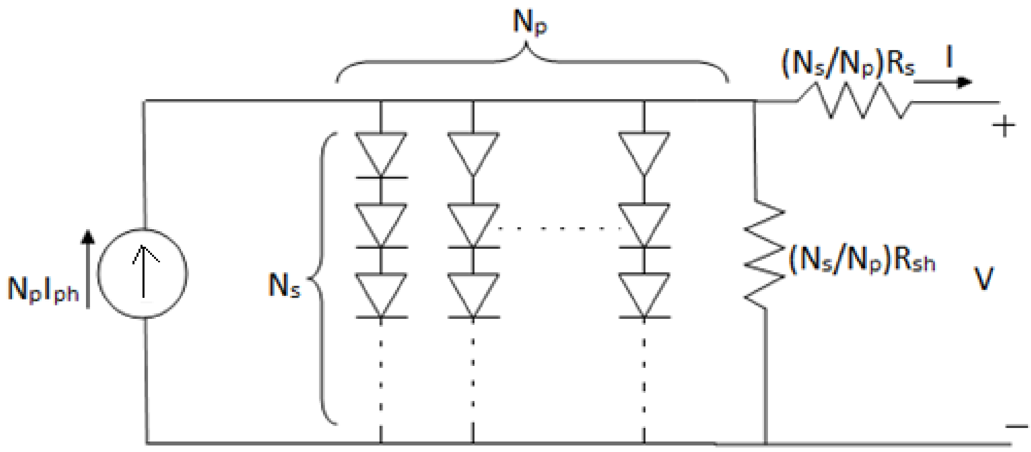


Figure 3.4: Equivalent circuit of solar array

3.4 *Photovoltaic Cell Characteristics*

The equivalent circuit shown in Figure 3.1 and described by Equation 3.4 represents a PV cell characteristic. Figure 3.5 show I-V curve of a practical photovoltaic device.

From Figure 3.5 we notice that there are three parameters that are very important on the PV characteristics:

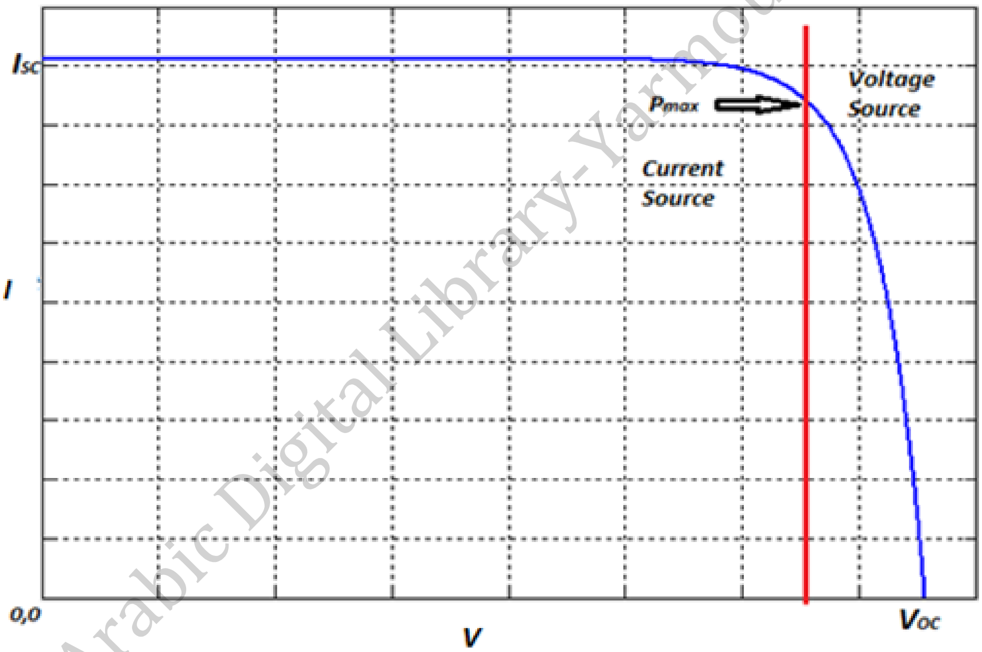


Figure 3.5: Characteristic I-V curve of a photovoltaic device

1. Short circuit current (I_{sc}): is the maximum current available at the terminals of the solar cell. It is produced by the short circuit conditions: V = 0. It can be represented with the series resistance R_S neglected by [10] [12].

$$I_{ph} = I_{sc} \qquad 3.10$$

From the equation of the short circuit current in equation 3.10, the value of the short circuit current depends linearly on the irradiation.

2. Open circuit voltage (V_{oc}): is the maximum voltage available at the terminals of the solar cell. It is produced by the open circuit conditions: I = 0 .It can be represented with shunt current I_{sh} neglected by [12].

$$V_{oc} = \frac{akT_c}{q}\ln(\frac{I_{ph}}{I_o}) = V_t\ln(\frac{I_{ph}}{I_o}) \quad 3.11$$

WhereV_t is the thermal voltage. From the equation of the open circuit voltage in equation 3.11, the value of the open circuit voltage depends logarithmically on the ratio $\frac{I_{ph}}{I_o}$. Thus, the value of the open circuit voltage depends logarithmically on the solar radiation. Equations 3.10 and 3.11 indicate that the short circuit current is higher affected by irradiation than the open circuit voltage.

3. Maximum power point (MPP): The power delivered by a PV cell attains a maximum value at the points (I_{mp},V_{mp}). I-V characteristic of the solar cell is used to determine the operating point at which the cell generates the maximum power. The MPP power is determined by calculating the product of the voltage and output current as illustrated in equation below [12], [42].

$$P_{max} = V_{max}I_{max} \quad 3.12$$

This point is located around the knee of the I-V characteristic. The solar cell is typically operated at or very close to the MPP in order to obtain the maximum power. A notice delivered from equation 3.12 that there is no power generated at either the short-circuit point or open-circuit point since there is zero voltage and current at the y-axis and x-axis respectively.

There are other parameters that also determine the PV performance:

1. Fill Factor (FF): It gives an indication of the quality of a cell's semiconductor junction and measures of how well a solar cell is able to collect the carriers generated by light. Fill Factor is the ratio of the maximum power that can be delivered to the load and the product of V_{oc} and I_{sc} as expressed in equation below [12]:

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} \quad 3.13$$

2. The efficiency (η): is defined as the ratio of the maximum output power P_{max} to the solar power received by the cell surface P_{in} as illustrated in equation below [12].

$$\eta = \frac{P_{max}}{P_{in}} = \frac{\mathrm{P_{max}}}{\mathrm{AG}} \quad 3.14$$

Where

A Cell Area (m^2)

G Ambient Radiation (W/m^2)

The characteristic of the PV array can be determined by multiplying the voltage of an individual cell by the number of cells connected in series and multiplying the current by the number of cells connected in parallel.

Electric generators are generally classified as current or voltage sources. The practical photovoltaic device presents a hybrid behavior, which may be of current or voltage source depending on the operating point [10]. The operating characteristic of a solar cell consists of two regions: the current source region and the voltage source region as shown in the characteristic curve in figure 3.5:

1. Current source region: This region is located on the left side of the I-V curve. It shows that the output current remains almost constant as the terminal voltage changes due to the low value of the load impedance of the solar cell.

2. Voltage source region: This region is located on the right side of the I-V curve. It shows that the output terminal voltage varies only minimally over a wide range of output current due to the high value of the load impedance of the solar cell.

3.5 Effect of Solar Radiation and Temperature

The performance of a solar PV system depends on the weather conditions. The output voltage, current and power of PV system vary as functions of solar radiation level and temperature [36]. Therefore the effects of these conditions could be considered in the design of PV arrays so that any change in temperature and solar radiation levels should not strongly affect the PV array output. The solar radiation at any location is strongly dependent on the orientation and inclination angles of the solar panel [38]. Location and time of the year are also factors that affect the output power of solar PV system.

For power system stability studies, a model of PV generation system requires incorporating the effect of solar radiation and temperature conditions that affect the dynamic output of solar cells. The current generated by sunlight considering solar radiation and temperature variations is illustrated in equation below [7], [40]:

$$I_{ph} = I_{sc}[1 + K_I (T_c - T_{ref})] \frac{G}{G_n} \qquad 3.15$$

Where:

I_{sc} Cell's short circuit current at a 25°C and 1000W/m^2,

K_I Cell's short circuit current temperature coefficient,

T_{ref} Cell's reference temperature,

G Irradiation on the device service (in W/m^2),

G_n Nominal irradiation (1000 W/m^2)

On the other hand, the cell's saturation current varies with the cell temperature, which is described as [7], [42].

$$I_o = I_{RS}\left(\frac{T_c}{T_{ref}}\right)^3 e^{\frac{qE_g\left(\frac{1}{T_{ref}}-\frac{1}{T_c}\right)}{ka}} \qquad 3.16$$

Where:

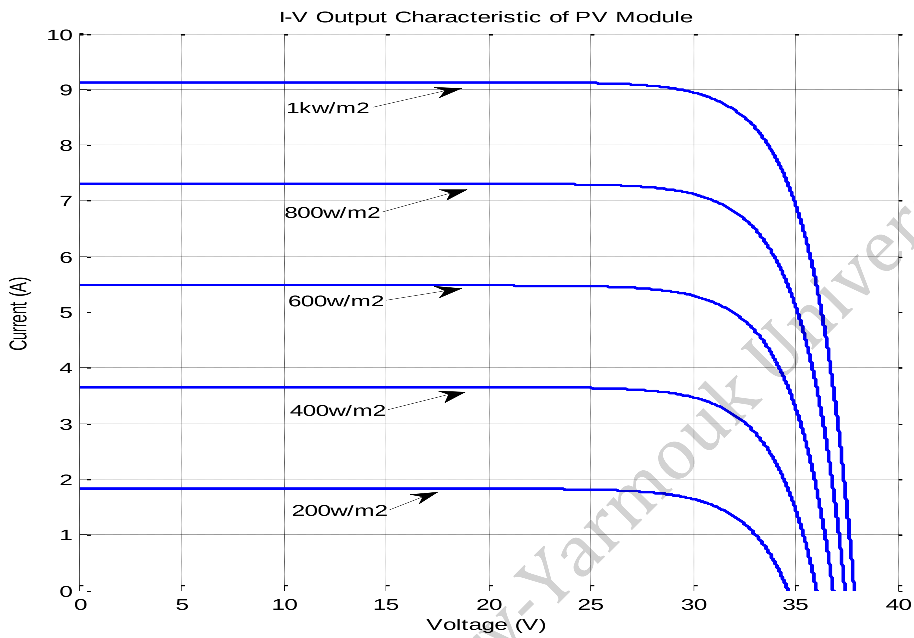
I_{RS} Cell's reverse saturation current at a reference temperature and a solar radiation,

E_g Band-gap energy of the semiconductor used in the cell

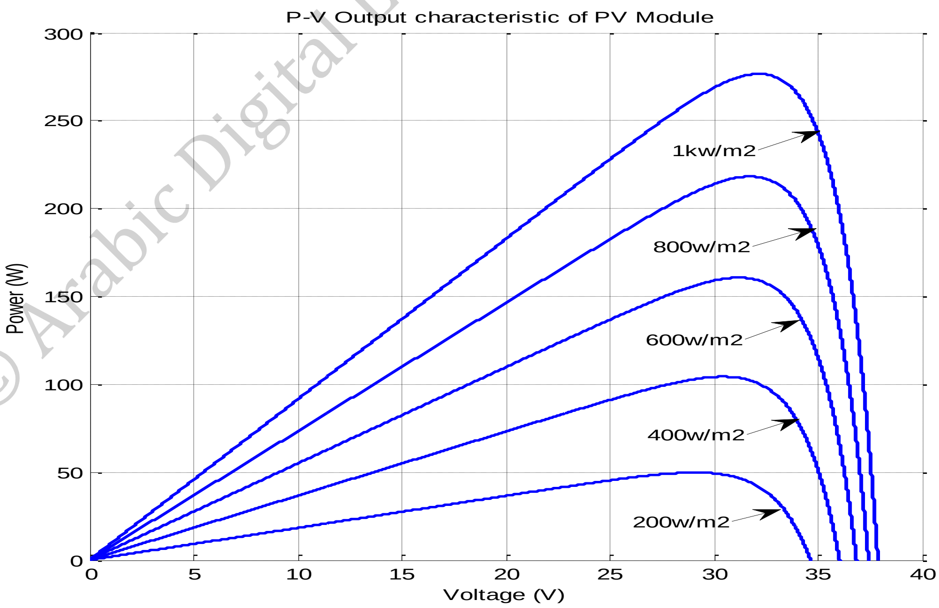
As pointed in equations 3.10 and 3.11, the short circuit current of the cell depends linearly on solar radiation while the open circuit voltage depends logarithmically on it. Thus, an increase in the radiation level of the PV cell has a logarithmical increase effect on the output voltage which leads to an increase in the output power of the solar PV cell. Whereas, an increase in the radiation level of the PV cell has a linear increase effect on the output current that leads to an increase in the output power of the solar PV cell [12]. These notations will be appeared in Figure 3.6 that shows the I-V and P-V characteristics of the solar module mentioned in the next chapter for solar radiation values 200, 400, 600, 800, and 1000 W/ m^2 at 25°C.

As illustrated in equations 3.15 and 3.16, the short circuit current of the cell depends logarithmically on operating temperature, while the open circuit voltage depends linearly on it. Thus, an increase in the operating temperature of the PV cell has a slightly increasing effect on the output current which leads to an increase in the output power of the solar PV cell. Whereas, an increase in the operating temperature of the PV cell has a logarithmical decrease effect on the output voltage that leads to a reduction in the output power of the solar PV cell [12]. These notations will be appeared in Figure 3.7 that shows the I-V and P-V characteristics of the solar module mentioned in the next chapter for temperature values 25, 35, 45, 55, and 65°C at 1000 W/m^2.

As shown Figure 3.6 and 3.7, the solar radiation mainly affects the output current, and the temperature mainly affects the output voltage.

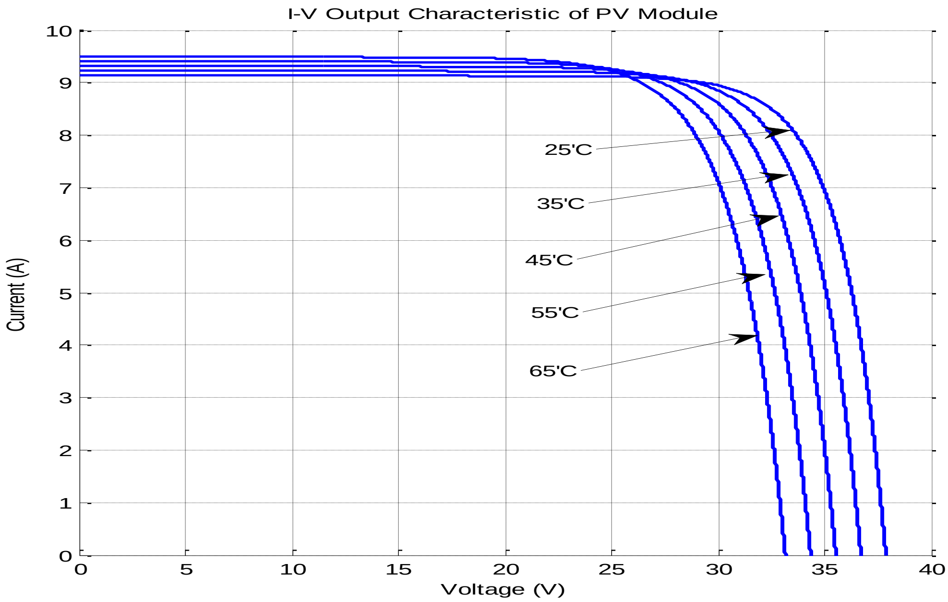


(a)

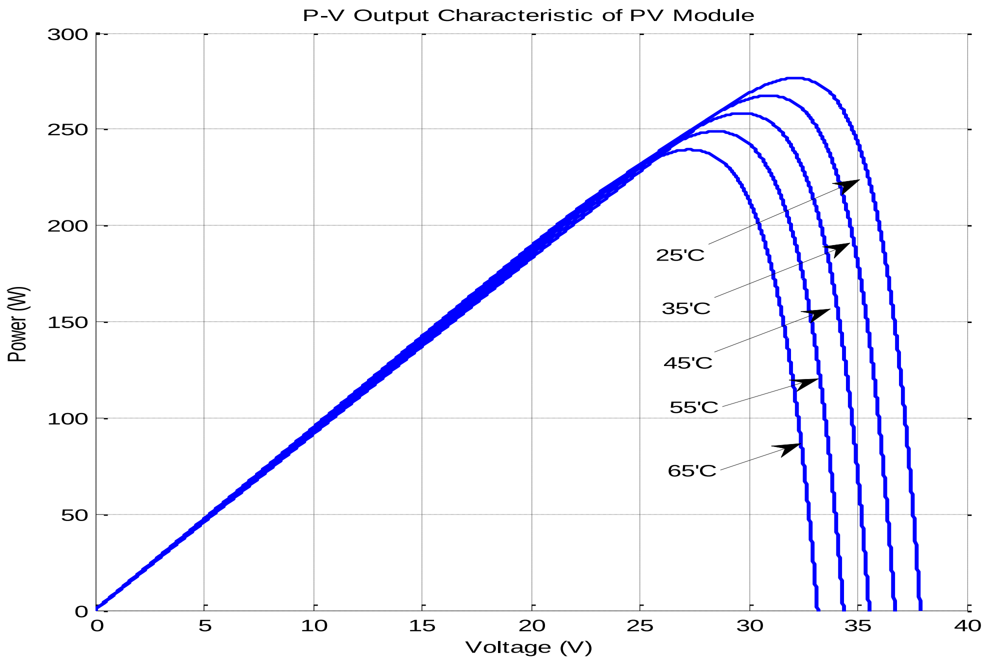


(b)

Figure 3.6: (a) I-V output characteristic of the solar module for different radiation values at 25°C. (b) P-V output characteristic of the solar module for different radiation values at 25°C.



(a)



(b)

Figure 3.7: (a) I-V Characteristic of the solar module for different temperature values at 1000W/m^2. (b) P-V Characteristic of the solar module for different temperature values at 1000W/m^2

3.6 Types of Photovoltaic Systems

There are mainly two types of Photovoltaic system: stand-alone systems and Grid connected systems as shown in Figure 3.8

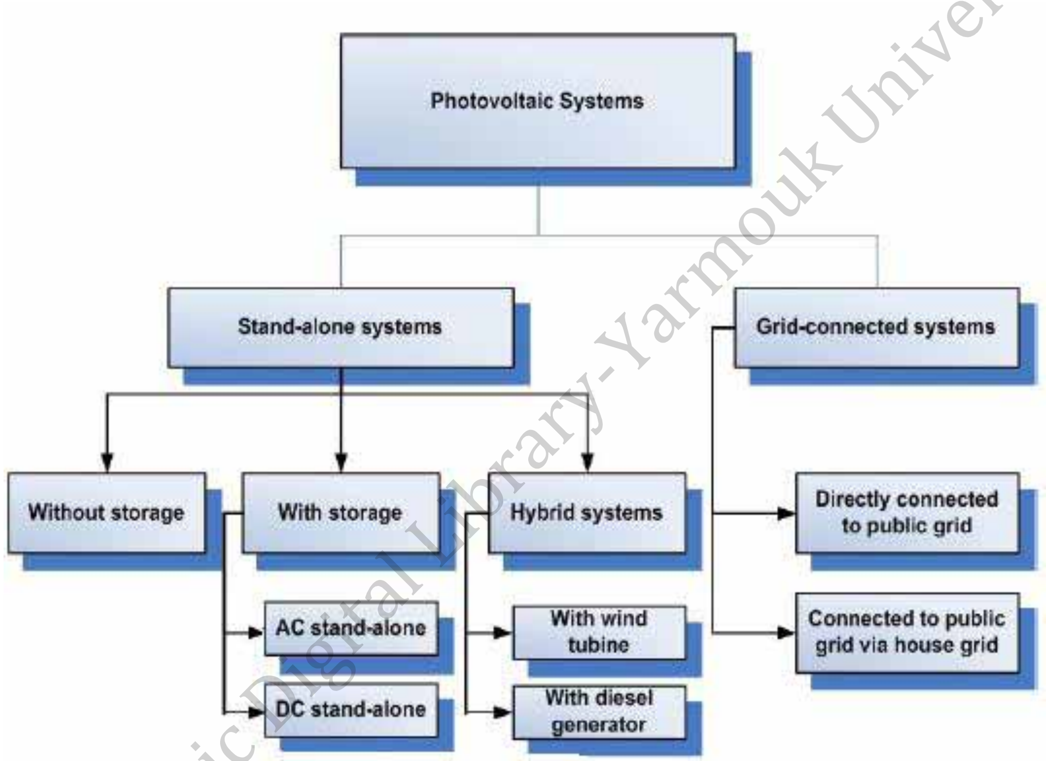


Figure 3.8: Types of photovoltaic systems

6.1 Stand Alone PV Systems (off-Grid Systems)

The majority of photovoltaic power generation applications are remote, off-grid applications. Stand alone systems are not connected to utility power lines and these are usually self sufficient systems. These systems are used in rural areas where no electricity network is available. These systems could either be used to charge the batteries that serve as an energy storage device or could work directly to loads [43].

3.6.2 Grid Connected PV Systems (on-Grid Systems)

A grid connected photovoltaic systems are designed to operate in parallel with the electric system grid, the main purpose of these systems is to reduce the electrical energy imported from the electric utility. In such PV systems, a two-way power flow can occur between the PV system and the electric utility network. This allows the AC power produced by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand. Also, this allows utility grid to feed the load during nights or when the electrical loads are greater than the PV system output. Figure 3.9 shows a diagram of the basic configuration of a grid-connected PV system. The primary component in grid connected PV systems is the inverter, which provides the interface between the photovoltaic array and the utility. Since the solar cell generates DC power while most of the loads require alternative AC power, the Inverter is used to convert the DC voltage generated by the solar cell into AC voltage at system frequency for grid-connected PV systems. Although PV power is generally more expensive than utility-provided power, the use of grid connected systems is increasing [44], [45], [46].

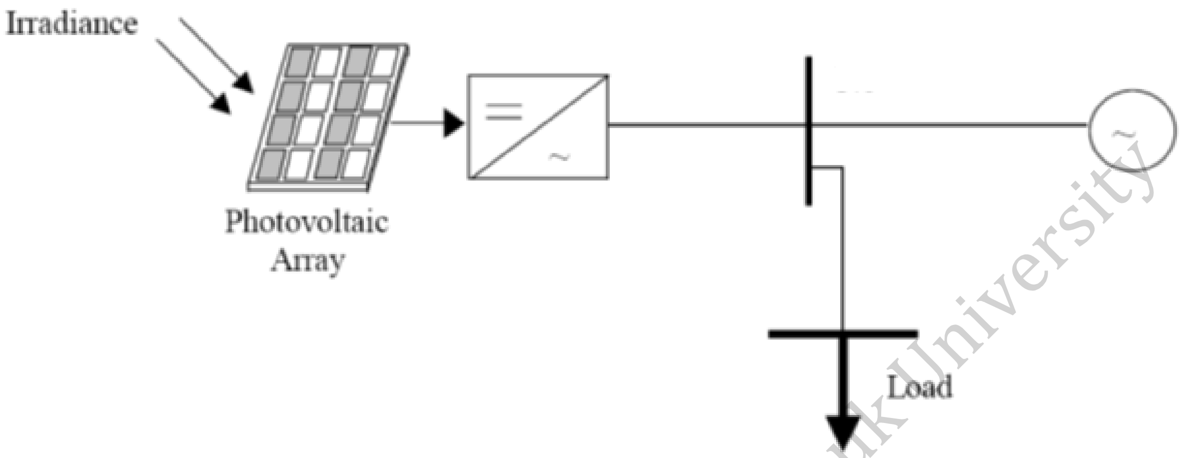


Figure 3.9: The basic configuration of a grid connected PV system

Grid connected PV systems can be classified in two groups: rooftop applications and large scale applications.

1. Rooftop systems are used to supply residential loads. These systems can be mounted on the roof.
2. Large scale systems are used to supply grid loads. These systems can be centralized or distributed systems.

CHAPTER FOUR

SYSTEM MODEL AND DATA PREPARATION

Ch.4 SYSTEM MODEL AND DATA PREPARATION

4.1 *Introduction*

In this work, IDECO system is taken as an example to study the effect of PV on voltage stability of system, the system configuration and parameters are introduced in this chapter in details. A distribution feeder is chosen to study significantly the impact of connecting a PV system on the voltage. Two programs are used to investigate the study results: CYME software and MATLAB program.

4.2 *Methodology*

1. The study was started with the collection of data, concerning the system parameters and solar PV module parameters.
2. Then, the model of PV system was performed to be connected to study system.
3. The PV system was connected to the selected feeder in the distribution grid using a power inverter.
4. CYME software is implemented to find the power flow, power losses, and feeder voltage profile curve before and after connecting the PV arrays, this step will be repeated at different penetrations of PV generation, different PV locations, and different solar radiation and temperature values.
5. MATLAB software is used to find the optimum size and location for PV system to investigate the minimum losses and best voltage profile.

4.3 CYME Power Engineering Software

CYME Power Engineering Software is a suite of applications composed of analysis modules. CYME software is important for some of the most advanced analysis for transmission, distribution and industrial power systems. CYME provides a list of functions of software solutions that addresses most aspects of power system analysis: power flow analysis, contingency analysis, optimal power flow analysis, fault analysis, harmonic analysis, transient stability analysis, breaker ratings analysis, wind energy conversion systems, voltage stability analysis, protective device coordination, and predictive and historical reliability assessment as shown in Figure 4.1.

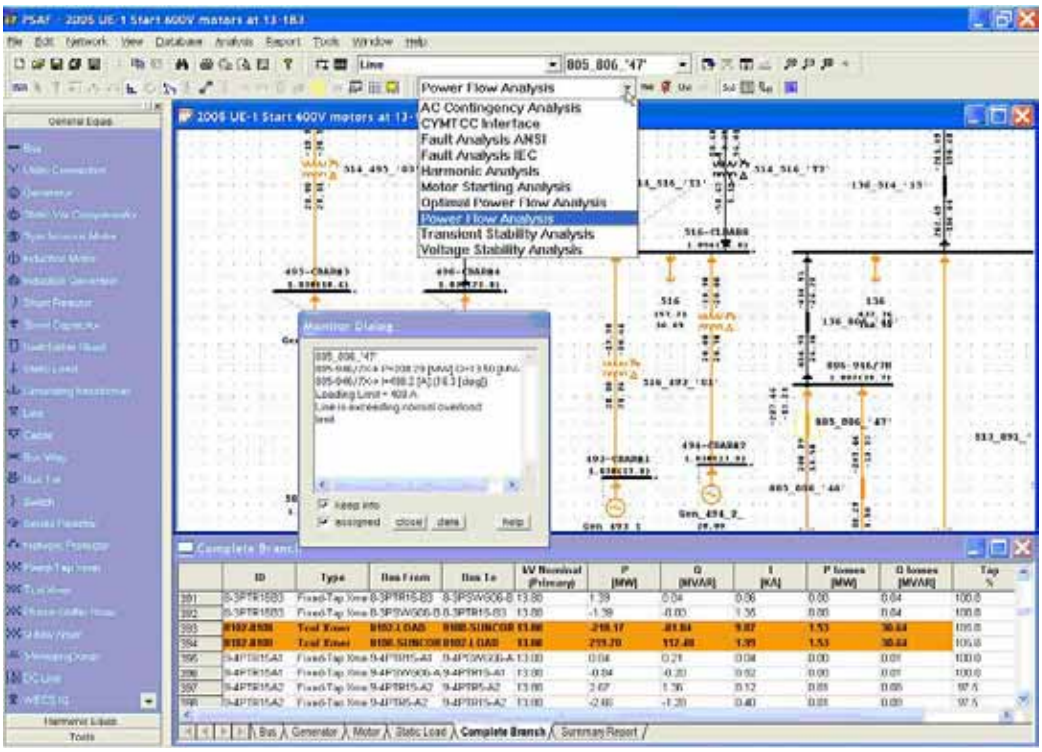


Figure 4.1: Shows list of functions of CYME software solutions

Power Flow Analysis of CYME:

The power flow analysis module of CYME power engineering software is used for the analysis of three-phase electric power networks. It is equipped with alternative solution techniques. The objective of a power flow program is to analyze the steady state performance of the power system under various operating conditions. It is the basic analysis tool for the planning, design and operation of any electrical power systems.

Power flow utilizes multiple solution algorithms as shown in Figure 4.2:

- Newton-Raphson
- Fast Decoupled
- Gauss-Seidel

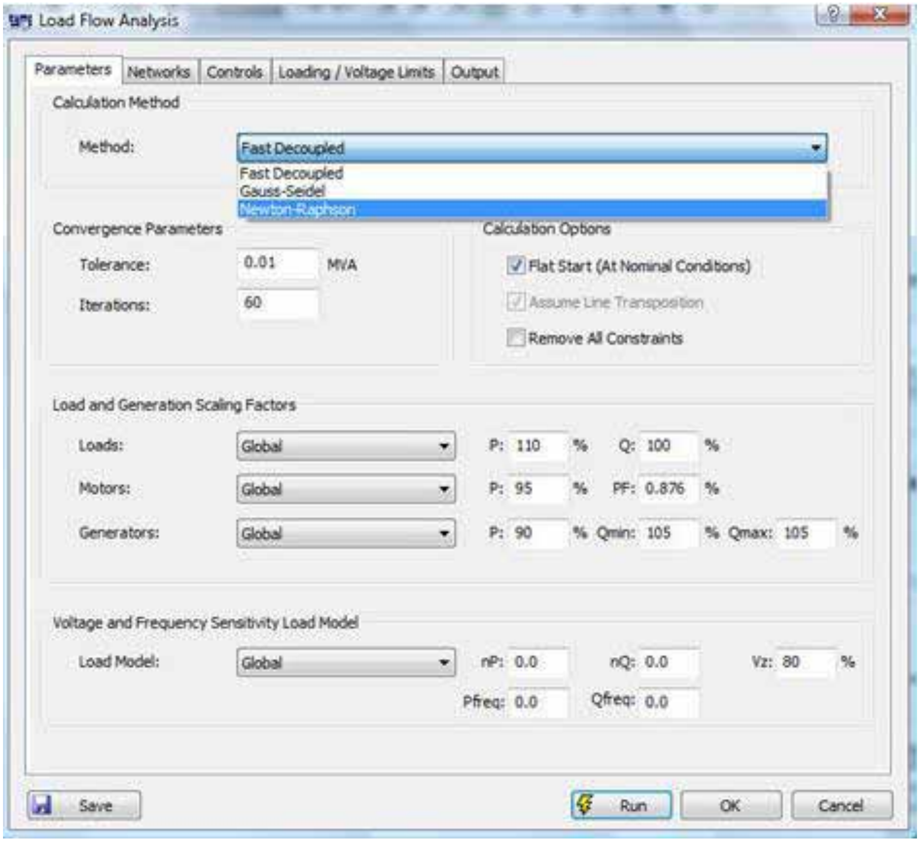


Figure 4.2: Multiple solution algorithms for power flow analysis

Analytical Capabilities:

- Analyzes networks with thousands of buses and branches.
- Multiple swing buses allowed.
- Local or remote control of voltage and reactive power flow through tap changing transformers.
- Cogeneration modeling includes:
  - Induction generators
  - Wind Energy Conversion Systems (WECS)
  - Photovoltaic systems

- Fuel cells
- Micro-turbines

- Capacitors with different control types.
- Global parameters to include or exclude any types of equipment from the analysis

4.4 MATLAB Software

MATLAB is a programming environment for algorithm development, data analysis, visualization, graphics, programming, and computation. MATLAB integrates these applications in a flexible open environment. Using MATLAB, you can solve technical computing problems faster than with traditional programming languages, such as C++. MATLAB offers expressions mathematically and visually for problems and their solutions. The users can use MATLAB in a wide range of applications, including:

1. Math, Statistics, and Optimization
2. Control System Design and Analysis
3. Signal Processing and Communications
4. Test & Measurement
5. Numeric computation and algorithm development
6. Modeling, simulation.
7. Data analysis and signal processing
8. Engineering graphics and scientific visualization
9. Application development, including graphical user interface building.

Figure 4.3 shows some useful contents of MATLAB software.

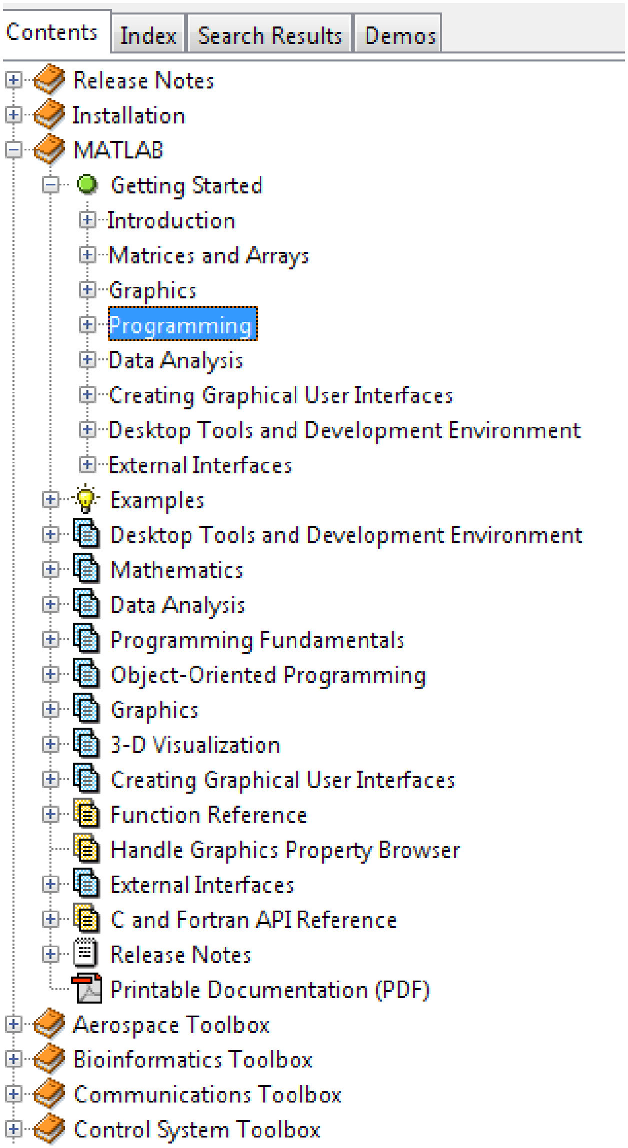


Figure 4.3: Some contents of MATLAB software

4.5 System Configuration and Parameters

Ajloun feeder (33 kv) was selected from IDECO system for this study. The configuration of this feeder is shown in Figure 4.4. To achieve the optimum size and location of PV system, the study feeder could be simplified and reduced as in Figure 4.5.

This feeder contains lots of distributed loads and transmission lines all the way along the feeder length. Table 4.1 shows the loads as real power demand (P) and reactive power demand (Q) for each node of the feeder. The impedance as resistance (R) and reactance (X) between each two nodes are shown in table 4.2.

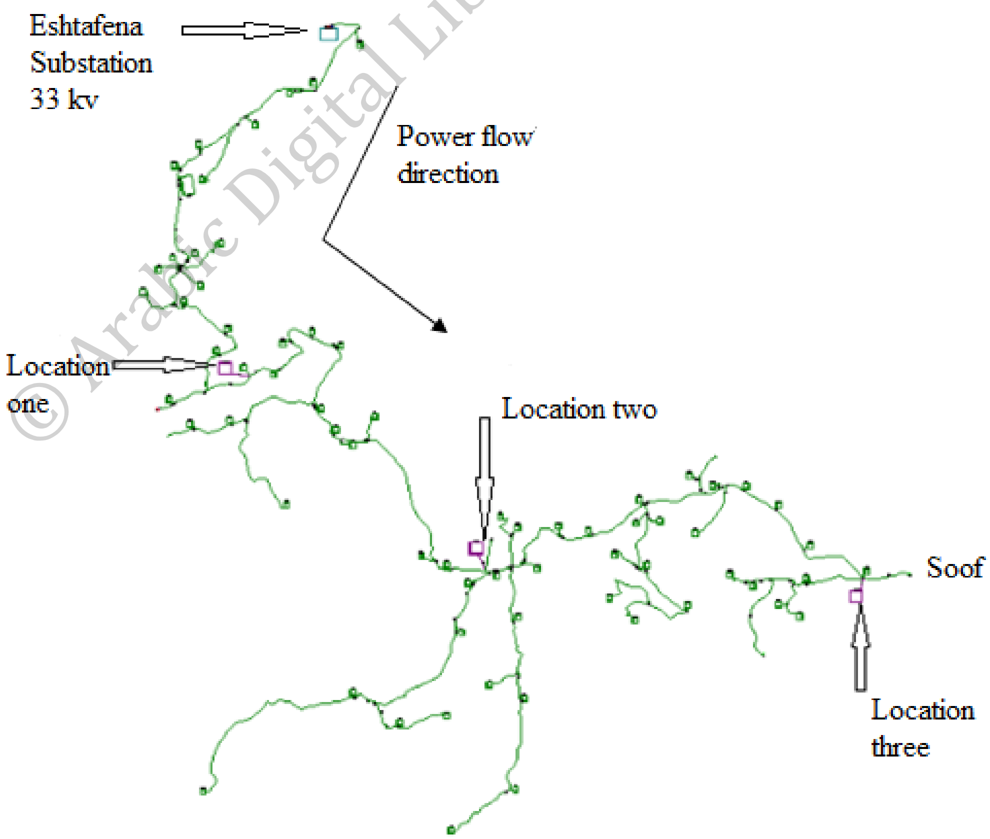


Figure 4.4: Configuration of Ajloun feeder

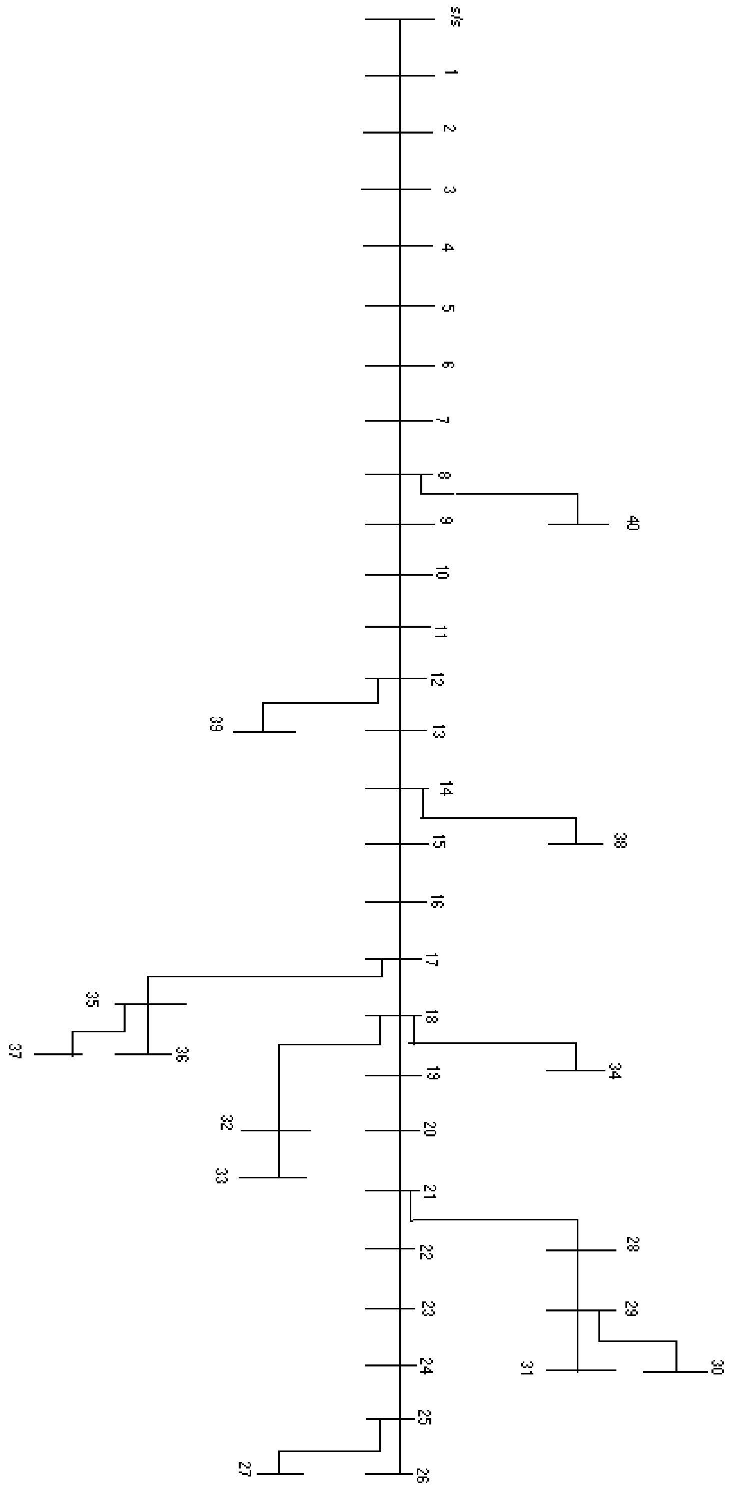


Figure 4.5: Simplified Ajloun feeder

Table 4.1: The loads for each node of Ajloun feeder

Node ID	Node Name	P (MW)	Q (MW)
1	00015331	0.13	0
2	00015333	0.04	0.04
3	00015335	0.36	0.23
4	00015337	0.13	0.08
5	00015339	0.08	0
6	13338	2.18	1.14
7	00015341	0.03	0.01
8	00015343	0.09	0.05
9	00015348	0.08	0.04
10	00015351	0.16	0.09
11	00015353	0.03	0
12	00015358	0	0
13	00015367	0.6	0.03
14	00015369	0	0
15	00015377	0.08	0.12
16	00015379	0.04	0
17	00015382	0	0
18	00015384	0	0
19	00015398	0.24	0.2
20	00015400	0.02	0.01
21	00015407	0	0
22	00015423	0.09	0.05
23	00015427	0.02	0.01
24	00015430	0.27	0.14
25	00015432	0	0
26	00015435	0.21	0.14
27	00015433	0.1	0.07
28	00015409	0.01	0
29	00015411	0	0
30	00015414	0.38	0.28
31	1596	0.25	0.21
32	00015393	0.09	0.05
33	00015396	0.03	0.02
34	00015402	0.42	0.18
35	00015387	0	0
36	00015390	0.01	0.01
37	00015388	0.17	0
38	00015374	0	0.1
39	00015359	0.71	0.03
40	1585	1.01	0

Table 4.2: The impedance between each two nodes of Ajloun feeder

From Node	To Node	Length (m)	R (ohm)	X (ohm)
1580	00015331	1556.4	0.349	0.402
00015331	00015333	1051.9	0.031	0.036
00015333	00015335	94.3	0.533	0.338
00015335	00015337	836.7	0.143	0.165
00015337	00015339	432.3	0.077	0.009
00015339	13338	232.5	0.436	1.329
13338	00015341	1390.9	0.033	0.054
00015341	00015343	146.7	0.08	0.42
00015343	00015348	34	0.022	0.025
00015348	00015351	65.8	0.212	0.245
00015351	00015353	639.6	0.808	0.982
00015353	00015358	2436.6	1.212	1.178
00015358	00015367	3081.8	0.38	0.438
00015367	00015369	1144.5	0.258	0.297
00015369	00015377	775.7	0.125	0.145
00015377	00015379	435.7	1.163	1.333
00015379	00015382	3492	0.102	0.117
00015382	00015384	307.2	0.09	0.104
00015384	00015398	271.7	0.342	0.394
00015398	00015400	1075.8	0.53	0.61
00015400	00015407	1595.9	0.462	0.532
00015407	00015423	492.2	0.577	0.666
00015423	00015427	1740.7	0.714	0.724
00015427	00015430	2154	0.098	0.113
00015430	00015432	312.4	0.147	0.17
00015432	00015435	444.7	0.411	0.303
00015432	00015433	764.4	0.071	0.082
00015407	00015409	214	0.31	0.357
00015409	00015411	933.8	0.615	0.708
00015411	00015414	1852.6	0.032	0.038
00015411	1596	97.8	0.617	0.711
00015384	00015393	1859.3	0.653	0.753
00015393	00015396	1969.6	0.172	0.199
00015384	00015402	519.9	2.886	3.775
00015382	00015387	3201.7	0.363	0.249
00015387	00015390	624.6	0.167	0.148
00015387	00015388	381.5	1.229	0.524
00015369	00015374	2235.4	0.191	0.22
00015358	00015359	575.6	0.024	0.015
00015343	1585	37.5	0.349	0.402

4.6 Solar PV Module Parameters

The solar PV module parameters used to perform PV arrays are provided by Philadelphia Company. These parameters are often provided with reference to the Standard Test Conditions (STC) of temperature and solar radiation. Table 4.3 shows the PV module parameters.

Table 4.3: Solar PV module parameters

Module:	203	Operator:	PSH
Name :	M60H250	#:	49216
Manufacture:	Philadelphia-solar	Product ID:	M60-MREL-28546
Current temp. coeff. (microA/cm^2/^{o}C):	4.03	Voltage temp. coeff. (mV/cell/^{o}C):	-2.30
Curve correction fac.(mOhm/cell/^{o}C):	0.05	Series resistance. (mOhm/cell) :	6.58
Cells area(cm^2):	243.36	Module area (m^2):	1.597360
Cells parallel:	1	Cells series:	60
Ambient temp. (^{o}C):	24.1	Sensor temp. (^{o}C):	22.8
Irradiation (W/m^2):	1000	Corrected temp. (^{o}C):	25.0
I_{sc} (A):	9.13	I_{mp} (A):	8.56
V_{oc} (V):	37.87	V_{mp} (V):	29.62
P_{mp}(W):	253	F.F. :	0.733
Cell eff.(%):	17.4	module eff.(%):	15.9
Shunt resistance (ohm):	273	Series resistance (mohm):	535

CHAPTER FIVE

SIMULATIONS RESULTS, AND DISCUSSIONS

Ch.5 SIMULATIONS RESULTS, AND DISCUSSIONS

5.1 Introduction

In this chapter, the results will be obtained and discussed to determine response of IDECO grid feeder to the connection of a PV arrays. The results will show the power flow and power losses in the studied feeder while PV arrays are connected at different penetrations of PV generation, feeder voltage profile will be also obtained at the same different penetrations of PV generation, where the results will be compared to the Base case without any penetration of PV generation. The same scenarios will be repeated for different values of solar radiation and temperature, and will be compared to the standard test conditions (1000 W/m^2 and 25^oC). Also, different locations for PV system along the feeder will be compared. The simulations and analysis will be discussed at the end of this chapter to show impact of grid connected PV on power flow, power losses, and voltage stability.

5.2 Power losses

5.2.1 Power Losses without Connecting PV Generation System (Base Case)

Power flow and losses analysis could be achieved at normal case without connecting PV arrays to investigate the purpose of this thesis. Table 5.1 shows the values of power generation by source, and feeder power losses in KW when no PV system is installed.

Table 5.1: Power Flow Study without PV Generation

Generation by source (KW)	10195.8
Generation by PV (KW)	0
Total generation (KW)	10195.8
Total load (KW)	9682.23
Total losses (KW)	348.42

5.2.2 Feeder Power Losses while Connecting Different Penetrations of PV Generation

Power flow and losses are simulated when connecting 1MW, 2MW, and 3MW PV Generation at end of the feeder at standard weather conditions (1000 W/m^2, 25^{o}C). Table 5.2 shows the power generation by source, and power losses in KW at different penetrations of PV generation.

Table 5.2: Power Flow Study with Different PV Generation at End of the Feeder

	1 MW	2 MW	3 MW
Generation by source (KW)	9301.44	8676.4	8346.64
Generation by PV (KW)	1000	1998	3000
Total generation (KW)	10301.44	10674.4	11346.44
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	268.01	242.73	310.87

From these results as shown in Figure 5.1, it is clear that the power losses become lower when penetration of PV generation is higher due to that the generation by the source decreases as the generation from PV system increases. At a high specific value of PV penetration, the power losses return to increase due to the fact that the PV system will supply the loads sited at beginning of the feeder.

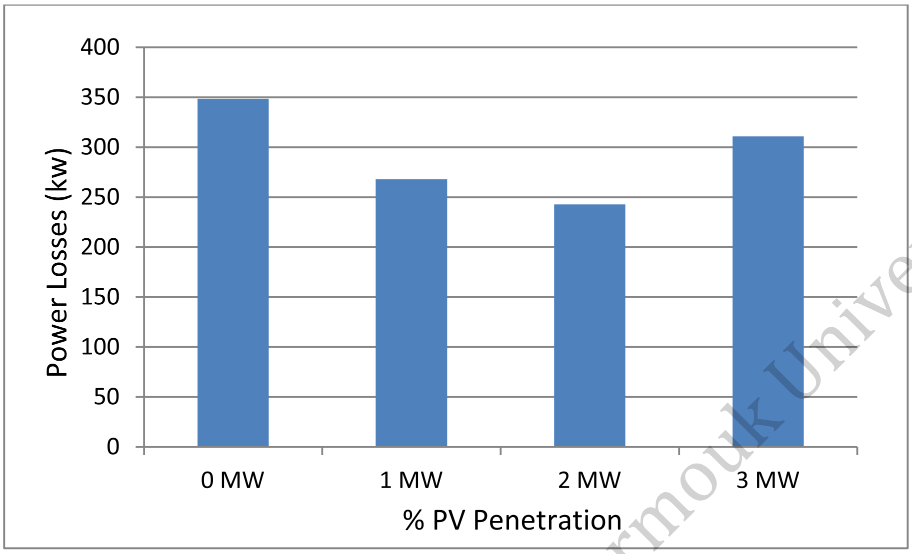


Figure 5.1: Power losses with different PV generation at end of the feeder

5.2.3 Feeder Power Losses at Different Locations for PV Generation

It is useful to find the power flow and losses at different locations along the feeder to determine the optimal location where the PV could be installed. Different power PV generation capacity 1MW, 2MW, and 3MW will be connected to the feeder at standard weather conditions at three locations:

- Location one: at a point near to the beginning of the feeder.
- Location two: at middle of the feeder.
- Location three: at the end of the feeder.

In the previous section, the PV system was connected at location three, where the PV system is located at location one and two in this section.

5.2.3.1 PV Generation at a point near to the beginning of feeder

Table 5.3 shows the power generation by source and power losses in KW while PV system with different penetrations of generation at standard weather conditions (1000 W/m^2 and 25^{o}C) is installed at a point near to the beginning of the feeder.

Table 5.3: Power flow study at a point near to the beginning of the feeder

	1 MW	2 MW	3 MW
Generation by source (KW)	9313.99	8661.07	8272.29
Generation by PV (KW)	1000	1998	3000
Total generation (KW)	10313.99	10659.07	11271.29
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	280.85	257.98	260.89

5.2.3.2 PV Generation at the middle of the feeder

Table 5.4 shows the power generation by source and power losses in KW when PV system with different penetrations of generation feeder at standard weather conditions (1000 W/m^2 and 25^{o}C) is installed at the middle of the.

Table 5.4: Power flow study with different PV generation at the middle of the feeder

	1 MW	2 MW	3 MW
Generation by source (KW)	9302.5	8660.38	8292.74
Generation by PV (KW)	1000	1998	3000
Total generation (KW)	10302.5	10658.38	11292.74
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	270.32	243.01	256.66

From these results as shown in Figure 5.2 (a) and (b), it is clear that the optimal location of the studied locations to reduce the total power losses is location three at end of the feeder when connecting 1MW and 2MW PV system as a result of load configuration at this location.

While connecting 3 MW PV system at the end of the feeder will lead to supply the near and far loads causing an increase in feeder power losses as shown in Figure 5.2 (c). So, the optimal location is location two at middle of the feeder due to supply the near loads by the PV generated power without transferring a valuable power for long distance.

The worst location is location three at the end of the feeder while connecting three 3MW due to the long distance needed to supply the loads by the PV generated power.

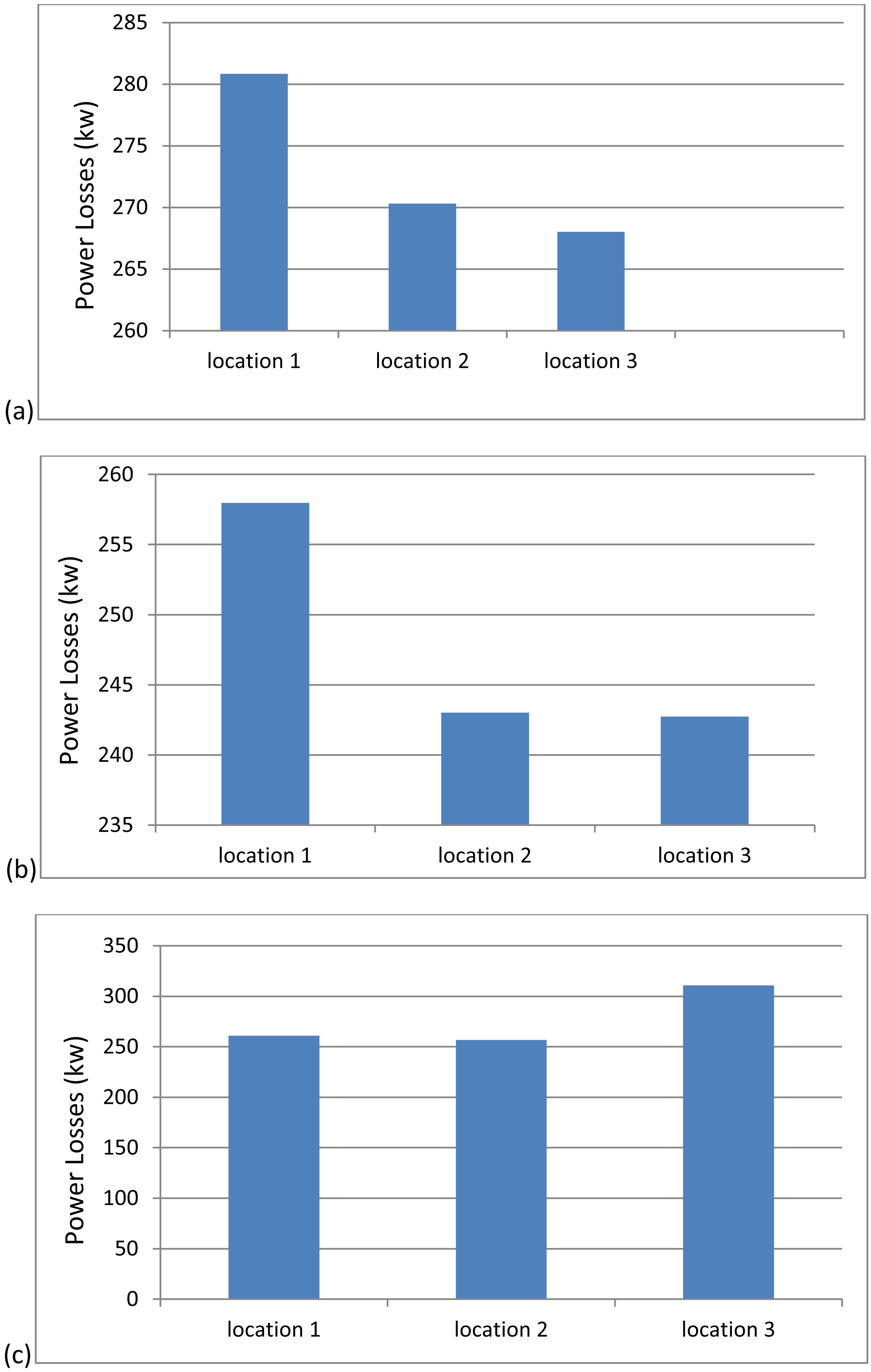


Figure 5.2: Power Losses with Different PV Generation at Different Location. (a) at 1MW PV Generation.(b) at 2 MW PV Generation. (c) at 3 MW PV Generation

5.2.4 Feeder Power Losses at Different Levels of Solar Radiation

During the day, the solar radiation is fluctuating during very short time. These variations could affect the power produced by PV arrays and the feeder power losses. PV generator is unlike conventional generator; it does not have rotating parts or inertia. Also, it does not have excitation system. So, a significant impact could occur in the system. In the previous sections, the power losses were found at standards conditions (1000 W/m^2). In this section, different solar irradiation 800 W/m^2, 600 W/m^2 , 400 W/m^2, and 200 W/m^2 at the end of the feeder with PV generation capacity 1MW, 2MW, and 3MW will be investigated.

5.2.4.1 Feeder Power Losses at 800 W/m^2 Solar Radiation

Table 5.5 shows the power generation by source and power losses in KW at 800 W/m^2 solar radiation with different penetrations of PV generation.

Table 5.5: Power Flow Study at 800W/m^2 with Different PV Generation

End of the Feeder		1 MW	2 MW	3 MW
Generation by source	(KW)	9449.25	8885.72	8470.97
Generation by PV	(KW)	802	1600	2399
Total generation	(KW)	10251.25	10485.72	10869.97
Total load	(KW)	9682.23	9682.23	9682.23
Total losses	(KW)	272.3	246.9	245.52

5.2.4.2 Power Losses at 600 W/m^2 Solar Radiation

Table 5.6 shows the power generation by source and power losses in KW at 600 W/m^2 solar radiation with different penetrations of PV generation.

Table 5.6: Power Flow Study at 600W/m^2 with Different PV Generation

	1 MW	2 MW	3 MW
Generation by source (KW)	9624.16	9050.47	8804.7
Generation by PV (KW)	599	1377	1799
Total generation (KW)	10223.16	10427.47	10603.7
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	283.29	254.18	248.47

5.2.4.3 Power Losses at 400 W/m^2 Solar Radiation

Table 5.7 shows the power generation by source and power losses in KW at 400 W/m^2 solar radiation with different penetrations of PV generation.

Table 5.7: Power Flow Study at 400W/m^2 with Different PV Generation

	1 MW	2 MW	3 MW
Generation by source (KW)	9801.29	9467.09	9184.87
Generation by PV (KW)	401	802	1199
Total generation (KW)	10202.29	10269.09	10383.87
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	295.18	274.19	260.63

5.2.4.4 Power Losses at 200 W/m^2 Solar Radiation

Table 5.8 shows the power generation by source and power losses in KW at 200 W/m^2 solar radiation with different penetrations of PV generation.

Table 5.8: Power Flow Study at 200W/m^2 with Different PV Generation

	1 MW	2 MW	3 MW
Generation by source (KW)	9993.88	9807.49	9634.77
Generation by PV (KW)	198	397	599
Total generation (KW)	10191.88	10204.49	10233.77
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	309.08	295.69	284.38

From these results as summarized in Figure 5.3 (a) and (b), it is clear that the feeder power losses become lower when the solar radiation is higher when 1MW and 2MW PV system is connected to the feeder because the output power for all solar radiation values is still below the optimum size of PV system.

While a 3 MW PV system is connected to the feeder as shown in Figure 5.3 (c), as the solar radiation increase, the output PV power increase until approximately reaches the value of the best of PV size. at solar radiation 1000 W/m^2 the power losses is the largest because the output power at this solar radiation exceeds the optimum size of PV system.

It is obvious that for a certain case of PV generation level, we can't conclude the relation between the solar radiation and the feeder losses because the feeder losses are PV size and location dependent.

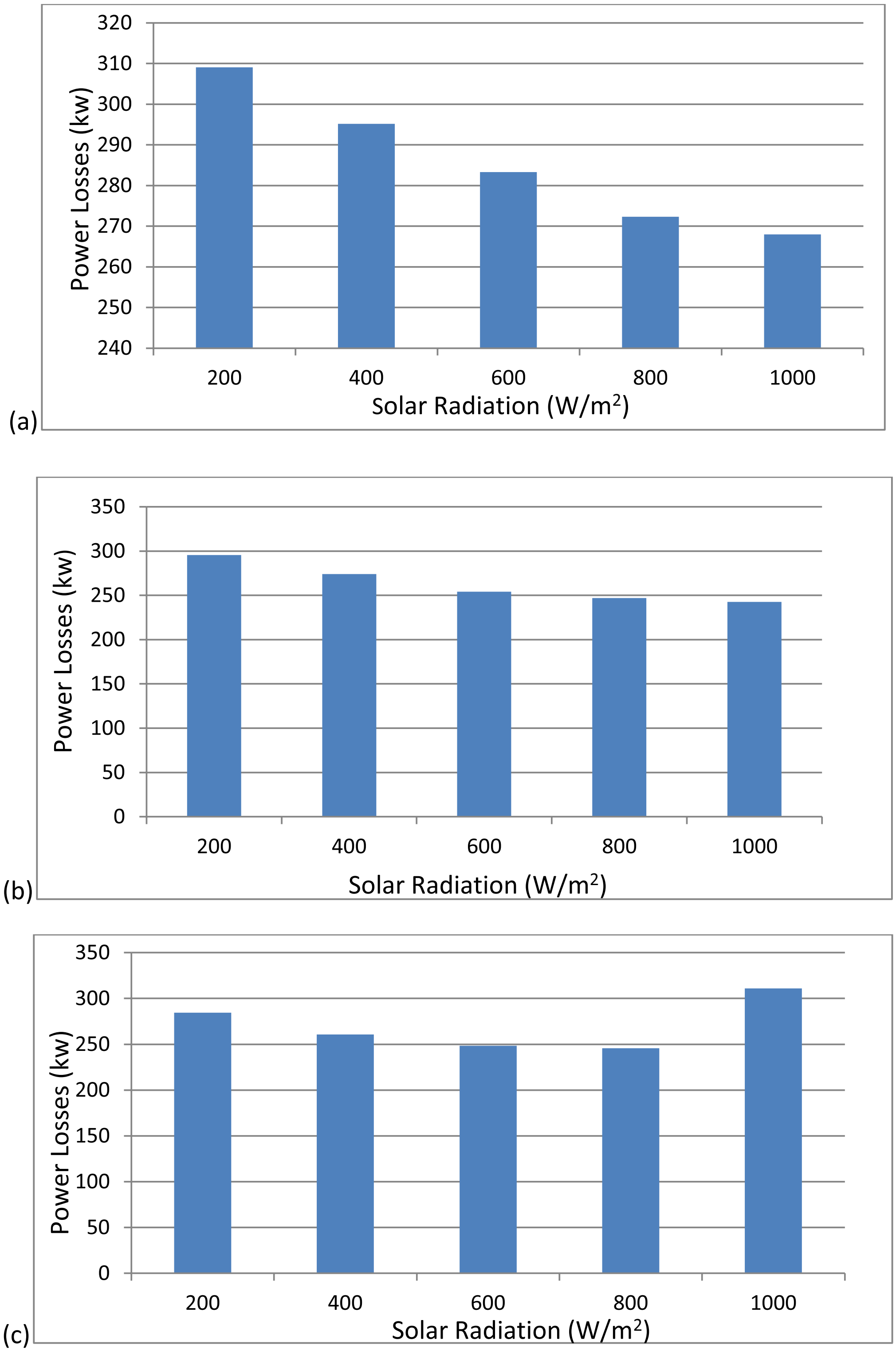


Figure 5.3: Power Losses at Different Solar Radiation.(a) at 1MW PV Generation. (b) at 2 MW PV Generation. (c) at 3 MW PV Generation

5.2.5 *Feeder Power Losses at Different Panel Temperatures*

Like the solar radiation, the temperature is fluctuating during the day. These variations could affect the power produced by PV arrays and feeder power losses. In the previous sections, the power losses were found at 25 °C. In this section, PV generation capacity 1MW, 2MW, and 3MW will be connected to the grid at different temperature 0 °C, 15 °C, 35 °C, and 50 °C at the end of the feeder.

5.2.5.1 *Feeder Power Losses at 0 °C Panel Temperature*

Table 5.9 shows the power generation by source and power losses in KW at 0°C temperature with different penetrations of PV generation.

Table 5.9: Power Flow Study at 0 °C with Different PV Generation

	1 MW	2 MW	3 MW
Generation by source (KW)	9282.66	8772.04	8756.71
Generation by PV (KW)	1096	2193	3286
Total generation (KW)	10378.66	10965.04	12042.71
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	266.75	236.74	417.54

5.2.5.2 *Feeder Power Losses at 15 °C Panel Temperature*

Table 5.10 shows the power generation by source and power losses in KW at 15°C temperature with different penetrations of PV generation.

Table 5.10: Power Flow Study at 15 °C with Different PV Generation

	1 MW	2 MW	3 MW
Generation by source (KW)	9354.52	8801.28	8533.63
Generation by PV (KW)	961	1923	2885
Total generation (KW)	10315.52	10724.28	11418.63
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	268.59	250.56	297.69

5.2.5.3 Feeder Power Losses at 35°C Panel Temperature

Table 5.11 shows the power generation by source and power losses in KW at 35°C temperature with different penetrations of PV generation.

Table 5.11: Power Flow Study at 35 °C with Different PV Generation

	1 MW	2 MW	3 MW
Generation by source (KW)	9384.16	8816.95	8472.55
Generation by PV (KW)	905	1810	2715
Total generation (KW)	10289.16	10626.95	11187.55
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	269.43	255.46	270.52

5.2.5.4 Feeder Power Losses at 50 °C Panel Temperature

Table 5.12 shows the power generation by source and power losses in KW at 50°C temperature with different penetrations of PV generation.

Table 5.12: Power Flow Study at 50 °C with Different PV Generation

	1 MW	2 MW	3 MW
Generation by source (KW)	9312.41	8782.7	8648.69
Generation by PV (KW)	1040	2080	3113
Total generation (KW)	10352.41	10862.7	11761.69
Total load (KW)	9682.23	9682.23	9682.23
Total losses (KW)	267.47	239.89	353.58

From these results as summarized in Figure 5.4 (a) and (b), it is clear that the feeder power losses become higher when the panel temperature is higher (i.e. PV output is lower) when 1MW and 2MW PV system is connected to the feeder because the output power for all temperature values is still below the optimum size of PV system.

While a 3 MW PV system is connected to the feeder as shown in Figure 5.3 (c), as the panel temperature increases, the output PV power decreases until it approximately reaches the value of the best of PV size (i.e. least losses). At all temperature values, the power losses increase because the output power at these temperature values is exceeded the optimum size of PV system.

It is obvious that for a certain case of PV generation level, we can't conclude the relation between the panel temperature and the feeder losses because the feeder losses are PV size and location dependent.

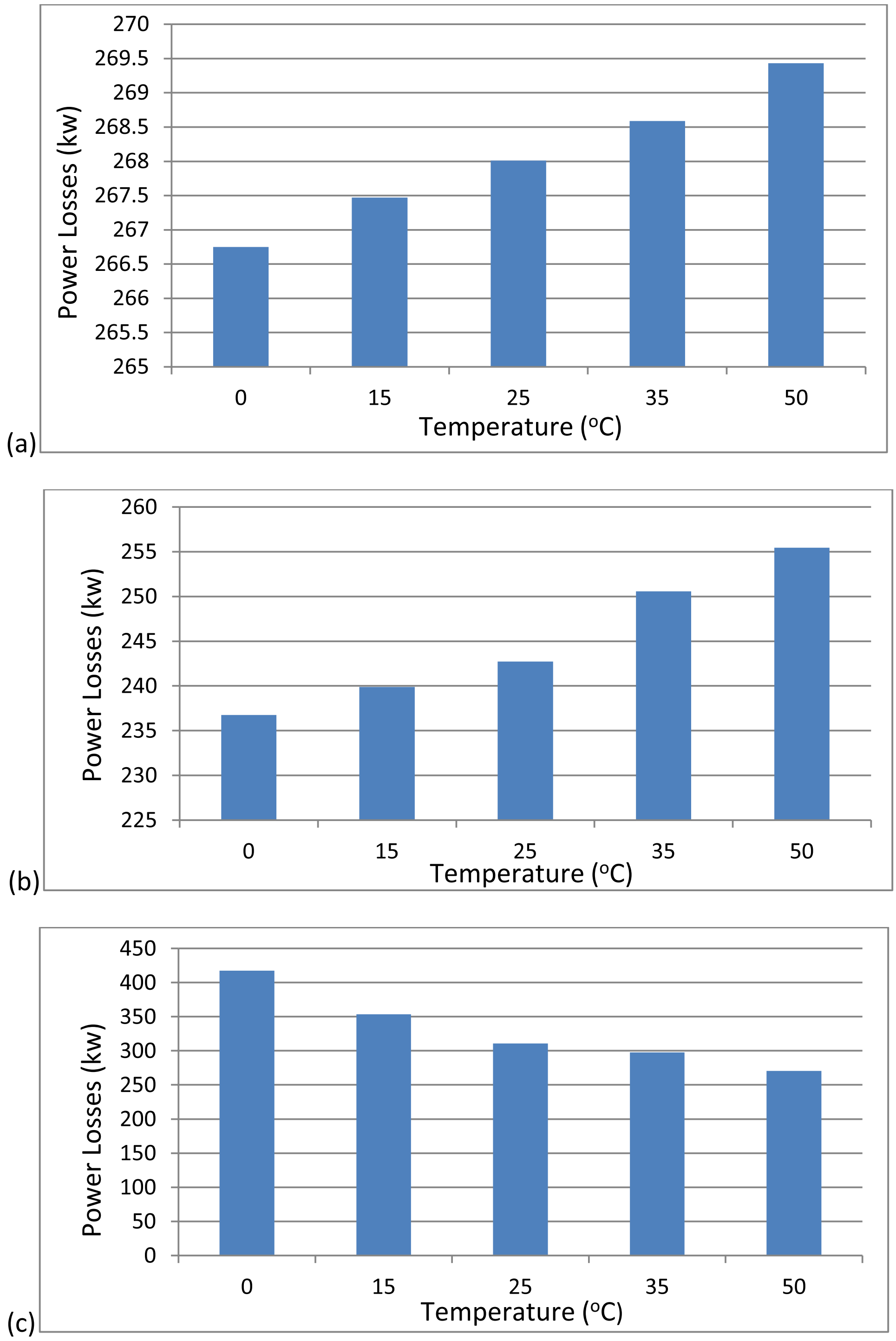


Figure 5.4: Power Losses at Different Panel Temperature.(a) at 1MW PV Generation. (b) at 2 MW PV Generation. (c) at 3 MW PV Generation

5.3 Voltage Profile

The selected feeder contains hundreds of nodes along its length. The voltage profile at these nodes was simulated and its corresponding curves according to the distance from the source were obtained.

5.3.1 Voltage Profile without Connecting PV System (Base Case)

Figure 5.5 shows the voltage profile curve for the studied feeder at normal case without connecting PV generation system. It is clear that the voltage at end of the feeder is poor.

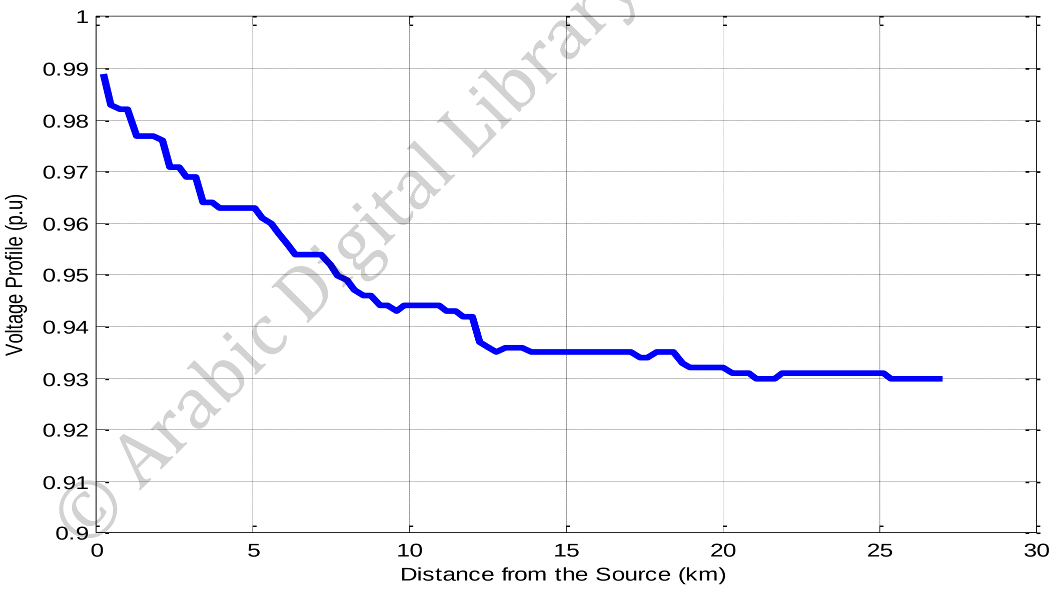


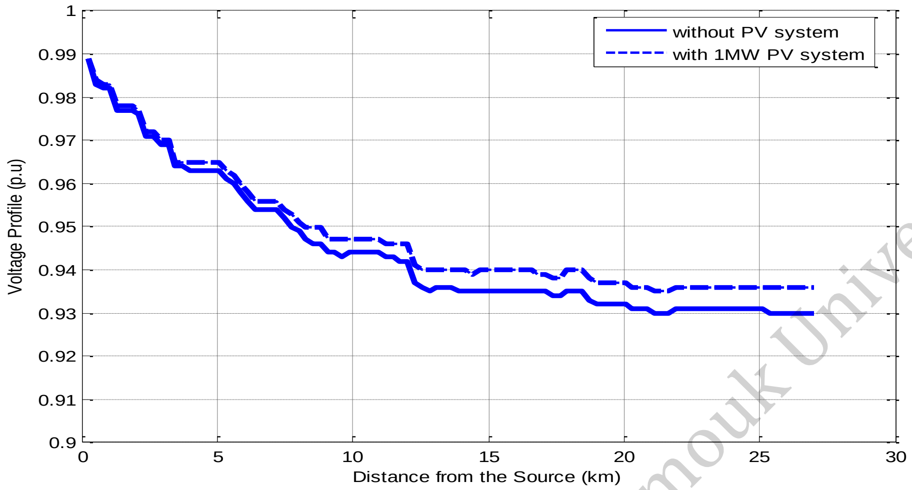
Figure 5.5: Voltage Profile Curve without PV Generation System.

5.3.2 Voltage Profile while Connecting Different Penetrations of PV System

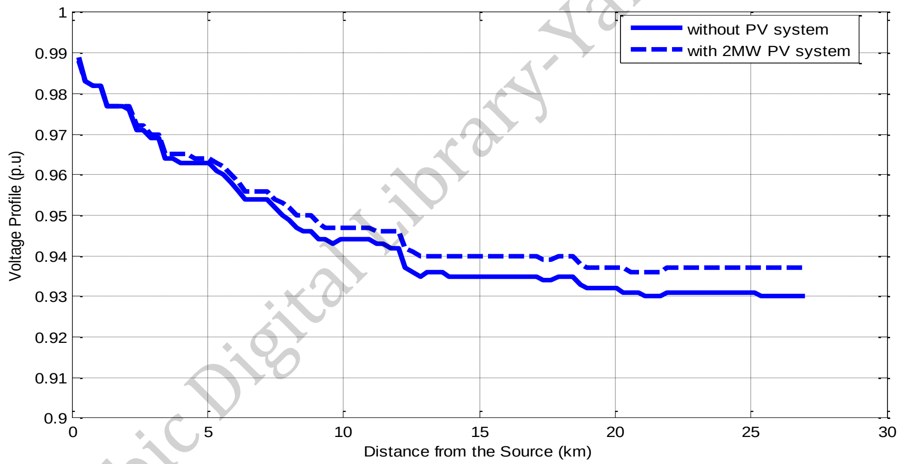
The voltage profile curves are achieved when connecting 1MW, 2MW, and 3MW PV generation system at the end of the feeder at standard weather conditions (1000 W/m^2, 25^{o}C).

Figure 5.6 shows the voltage profile curve at 1 MW, 2 MW, and 3 MW of PV generations. A comparison between these curves is shown in figure 5.7.

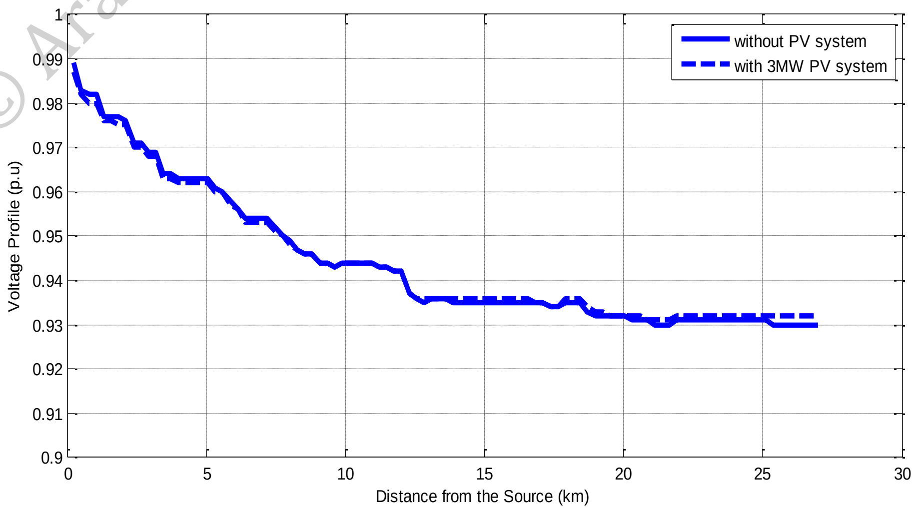
From these results as shown in Figure 5.6 and 5.7, it is clear that the voltage profile could be improved when 1 MW is connected to the feeder, and more improvement could be occurred when 2 MW of PV system is connected. At 3 MW, a small improvement could be occurred on voltage profile. In other words; as the PV penetration is increased, the voltage profile is improved until a specific value of penetration of PV generation is reached which start to decrease the voltage profile.



(a)



(b)



(c)

Figure 5.6: Voltage Profile Curve with PV Generation System.(a) 1MW PV System. (b) 2MW PV System (c) 3MW PV System.

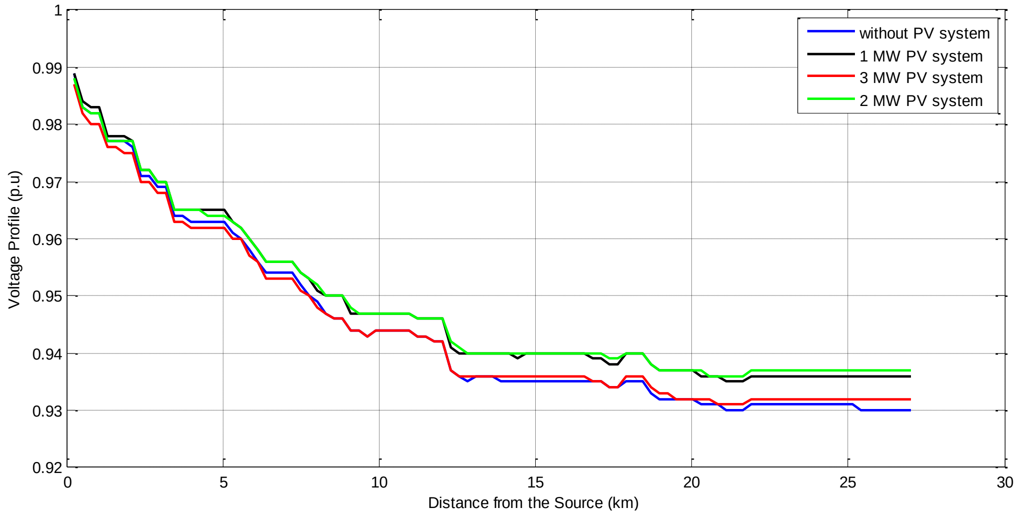


Figure 5.7: Comparison between Voltage Profile Curves at different penetrations of PV Generation.

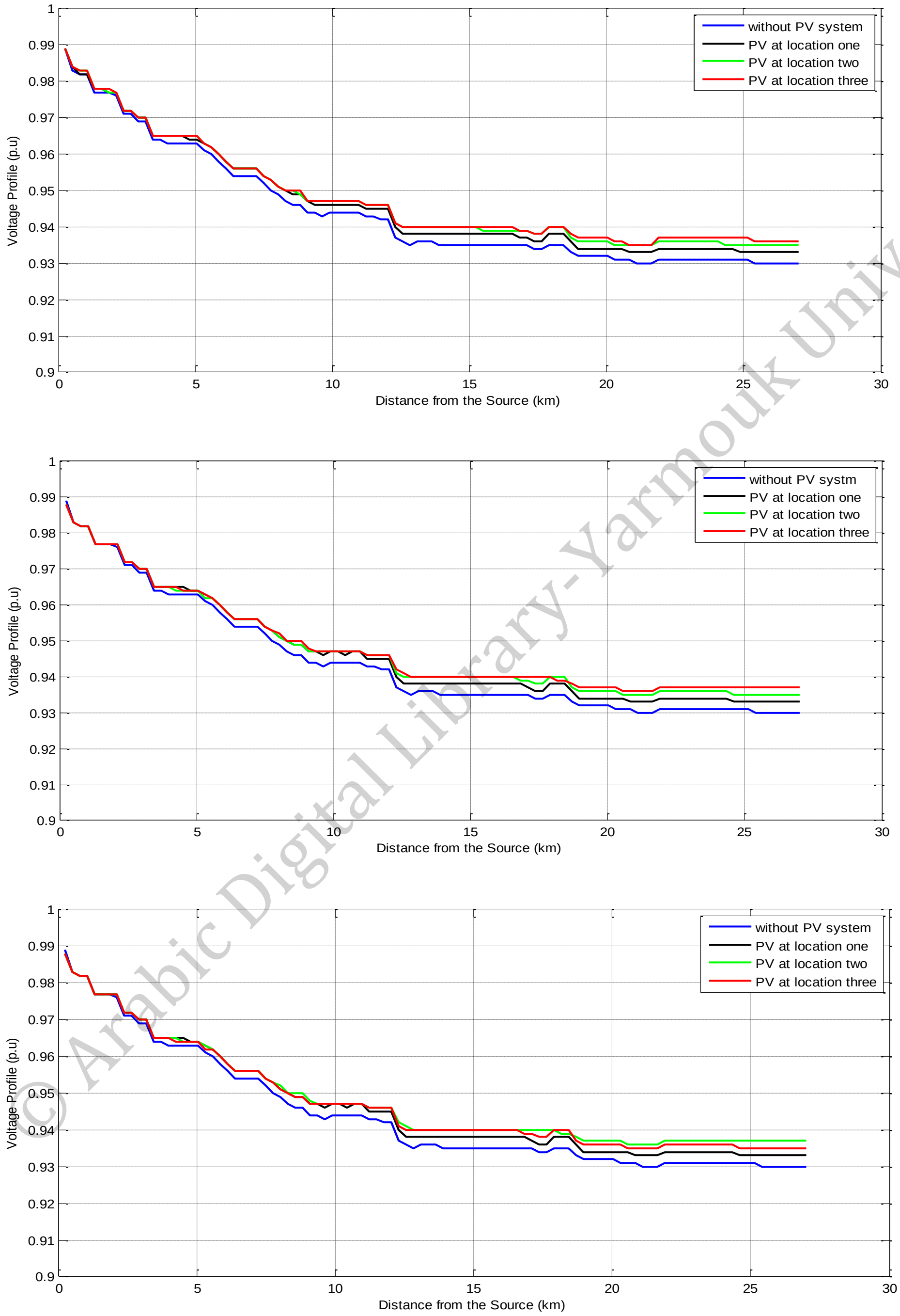
The percent of voltage improvement at the end of the feeder at different penetrations of PV generation is illustrated in table 5.13.

Table 5.13: The percent of voltage improvement at different penetrations of PV generation

% PV Penetration	1MW	2MW	3MW
% Voltage Improvement	0.65 %	0.75 %	0.22 %

5.3.3 Voltage Profile at Different Locations of PV System

Figure 5.8 shows the voltage profile curves for the feeder when PV system is installed at three locations on the feeder (beginning, middle, and end of the feeder) at standard weather conditions at different penetrations of PV system.



(a)

(b)

(c)

Figure 5.8: Comparison between Voltage Profile Curves when PV System is installed at different locations with different penetrations. (a) 1MW PV penetration (b) 2MW PV penetration (c) 3MW PV penetration

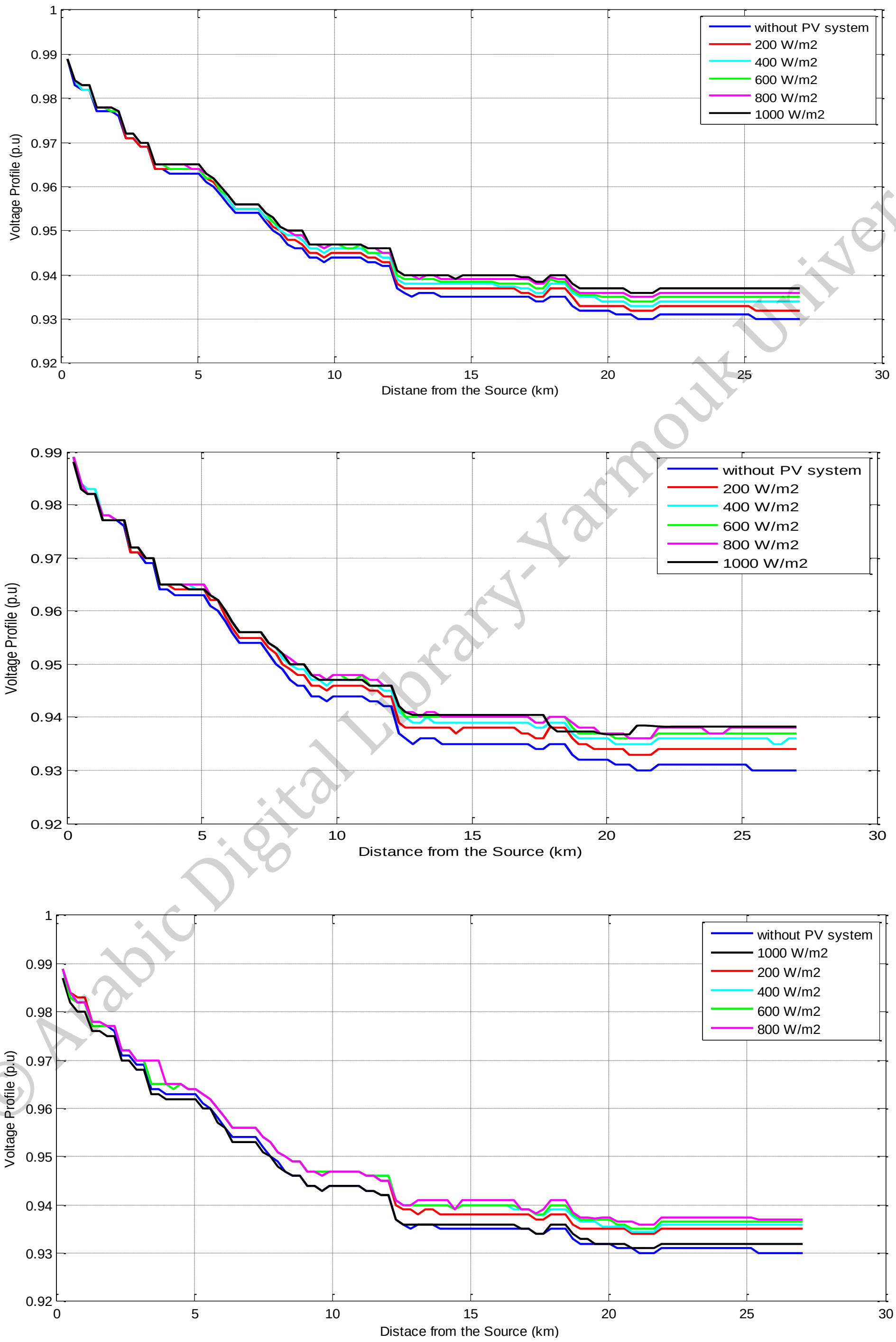
It is clear from Figure 5.8 that the optimum location from the three locations is at the end of the feeder when 1MW or 2MW PV generation system is connected to grid, where the optimum location is at middle of the feeder while 3MW PV connected system. The percent of voltage improvement at the end of the feeder at different locations of PV generation is illustrated in table 5.14.

Table 5.14: The percent of voltage improvement at different locations of PV generation

	% Voltage Improvement		
Location	1 MW	2 MW	3 MW
Location one	0.32 %	0.32 %	0.32%
Location two	0.54 %	0.54 %	0.74%
Location three	0.65 %	0.75 %	0.55%

5.3.4 Voltage Profile at Different Levels of Solar Radiation

Figure 5.9 shows the feeder voltage profile curves while PV system is installed at the end on the feeder at different solar radiation: 1000 W/m^2, 800 W/m^2, 600 W/m^2, 400 W/m^2, and 200 W/m^2.



(a)

(b)

(c)

Figure 5.9: Comparison between Voltage Profile Curves while PV System is installed at different solar radiation with different penetrations. (a)1MW PV penetration (b) 2MW PV penetration (c) 3MW PV penetration

It is clear in figure 5.9 that as the solar radiation increases, the voltage profile is improved. At 3 MW, the voltage profile at 1000 W/m^2 solar radiation is the worst among the other solar radiation levels. The percent of voltage improvement at the end of the feeder at different solar radiation is illustrated in table 5.15.

Table 5.15: The percent of voltage improvement at different solar radiation

	% Voltage Improvement		
Solar Radiation	1 MW	2 MW	3 MW
1000 W/m^2	0.75 %	0.89 %	0.22 %
800 W/m^2	0.65 %	0.86 %	0.75 %
600 W/m^2	0.54 %	0.75 %	0.70 %
400 W/m^2	0.43 %	0.65 %	0.65 %
200 W/m^2	0.22 %	0.43 %	0.54 %

5.3.5 Voltage Profile at Different Variation of Panel Temperature

The variation of panel temperature has a smaller effect than that for the variations of solar radiations. 2 MW PV generation system could be presented here to show this effect. Figure 5.10 shows the feeder voltage profile curves while PV system is installed at the end on the feeder at different solar radiations: 0 °C, 15 °C, 25 °C, 35 °C, and 50 °C.

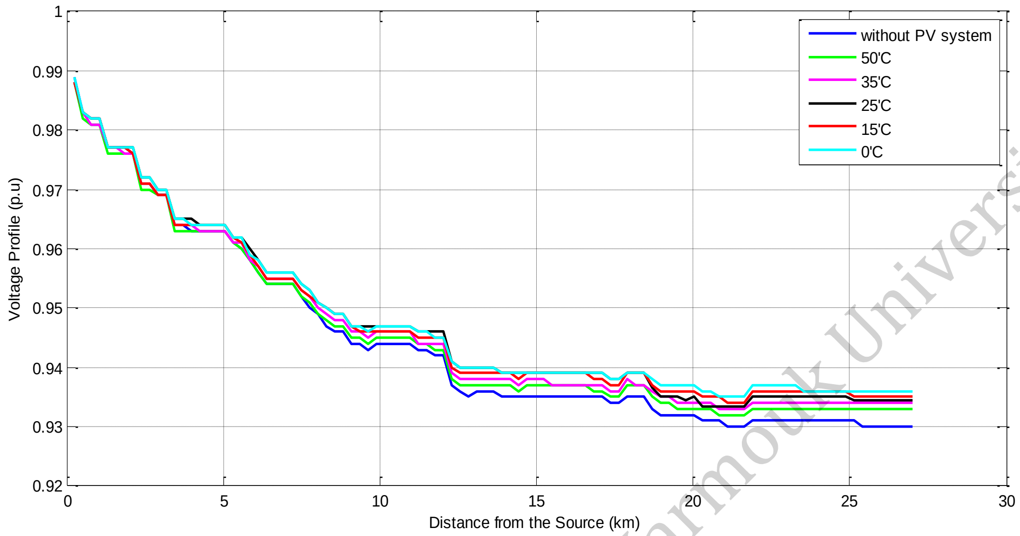


Figure 5.10: Comparison between Voltage Profile Curves when PV System is installed at different temperature with 2MW PV penetration

As shown in Figure 5.10, the voltage profile curve is improved as the panel temperature decreases. The percent of voltage improvement at the end of the feeder at different panel temperature is illustrated in table 5.16.

Table 5.16: The percent of voltage improvement at 2MW at different panel temperature

Temperature	0 °C	15 °C	25 °C	35 °C	50 °C
% Improvement	0. 65 %	0.54 %	0.50 %	0.43 %	0.32 %

5.4 *Photovoltaic System Sizing and Allocation*

PV generation system on distribution systems achieves many benefits such as reducing power losses and improving voltage profile. For a particular node, as size of PV generation system is increased, the losses start to reduce to a minimum value. If the size of PV system is further increased, the losses start to increase and may exceed the losses of the normal case without connecting a PV system [47].

Size and location of PV system are important factors in the application of PV for losses minimization and voltage improvement. Inappropriate selection of size and location of PV system may be possible to increase the losses in the system and to achieve a poor voltage profile. So, it is very important to optimize size and location of the PV system on distribution systems to reduce the losses and improve the voltage profile. There are set of indices is proposed to quantify benefits of distributed generation as voltage sensitivity index and Line losses index [47], [48].

In this study, a methodology based on load flow is presented to determine the proper size and location of PV system. The proper location is found by coupling between decreasing the power losses and improving the voltage profile of the system. This methodology is a fast method to identify the best location [47].

This methodology will propose with only one power flow calculation. This methodology creates the optimum size for each node with the smallest power losses and the best voltage profile.

This methodology also selects the optimum location according to the result priority list of sensitive node to power losses and voltage profile [47].

5.4.1 Exact Loss Formula

The real power loss in a system is given by equation 6.1. This called "exact loss" formula [48].

$$P_l = \sum_{i=1}^{n}\sum_{j=1}^{n}[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}(Q_iP_j - P_iQ_j)] \qquad 6.1$$

Where:

$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i - \delta_j)$

$\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin(\delta_i - \delta_j)$

$Z_{ij} = r_{ij} + jx_{ij}$ is the ijth element of $[Z_{bus}]$

$P_i = P_{Gi} - P_{Di}$

$Q_i = Q_{Gi} - Q_{Di}$

P_{Gi} and Q_{Gi} are the injection powers of PV generators to the node

P_{Di} and Q_{Di} are the load demand

P_i and Q_i are the active and reactive power of the nodes.

The sensitivity factor α_i of real power loss with respect to real power injection from PV system is given by:

$$\alpha_i = \frac{\partial P_l}{\partial P_i} = 2\sum_{j=1}^{n}(\alpha_{ij}P_j - \beta_{ij}Q_j) \qquad 6.2$$

At minimum losses, the rate of change of losses with respect to injected power (sensitivity factor) becomes zero

$$\alpha_i = \frac{\partial P_l}{\partial P_i} = 2\sum_{j=1}^{n}(\alpha_{ij}P_j - \beta_{ij}Q_j) = 0$$

It follows that

$$\alpha_{ii}P_i - \beta_{ii}Q_i + \sum_{j=1, j\neq i}^{n}(\alpha_{ij}P_j - \beta_{ij}Q_j) = 0$$

$$P_i = \frac{1}{\alpha_{ii}}\,[\beta_{ii}Q_i - \sum_{j=1, j\neq i}^{n}(\alpha_{ij}P_j - \beta_{ij}Q_j)]$$

Due to that $P_i = P_{Gi} - P_{Di}$, its result that:

$$P_{Gi} = P_{Di} + \frac{1}{\alpha_{ii}}\,[\beta_{ii}Q_i - \sum_{j=1, j\neq i}^{n}(\alpha_{ij}P_j - \beta_{ij}Q_j)] \quad 6.3$$

The above equation gives the optimum size of PV for each node i to minimize the power losses. Any size of PV other than P_{Gi} placed at node i, will lead to higher loss.

5.4.2 Method Procedure

1. Run the normal case load flow and use its results to complete the other steps.
2. Calculate the optimum size for each node using equation 6.3.
3. Calculate the power losses using equation 6.1 by placing a PV system of optimum size obtained in step 2 for that node.

4. Rank the nodes from the minimum losses to the maximum one.
5. Rank the nodes from the minimum voltage to the maximum one according to normal case power flow.
6. The ranks from step 4 and step 5 are used to get a new rank by comparison between them.
7. Choose the best place according to the smaller rank from step 6.

5.4.3 Method Results

According to method procedure, the optimum Size of PV system at various nodes for Ajloun feeder was found. The optimum sizes ranging from 0.62 to 8.25 MW as shown in Figure 6.1.

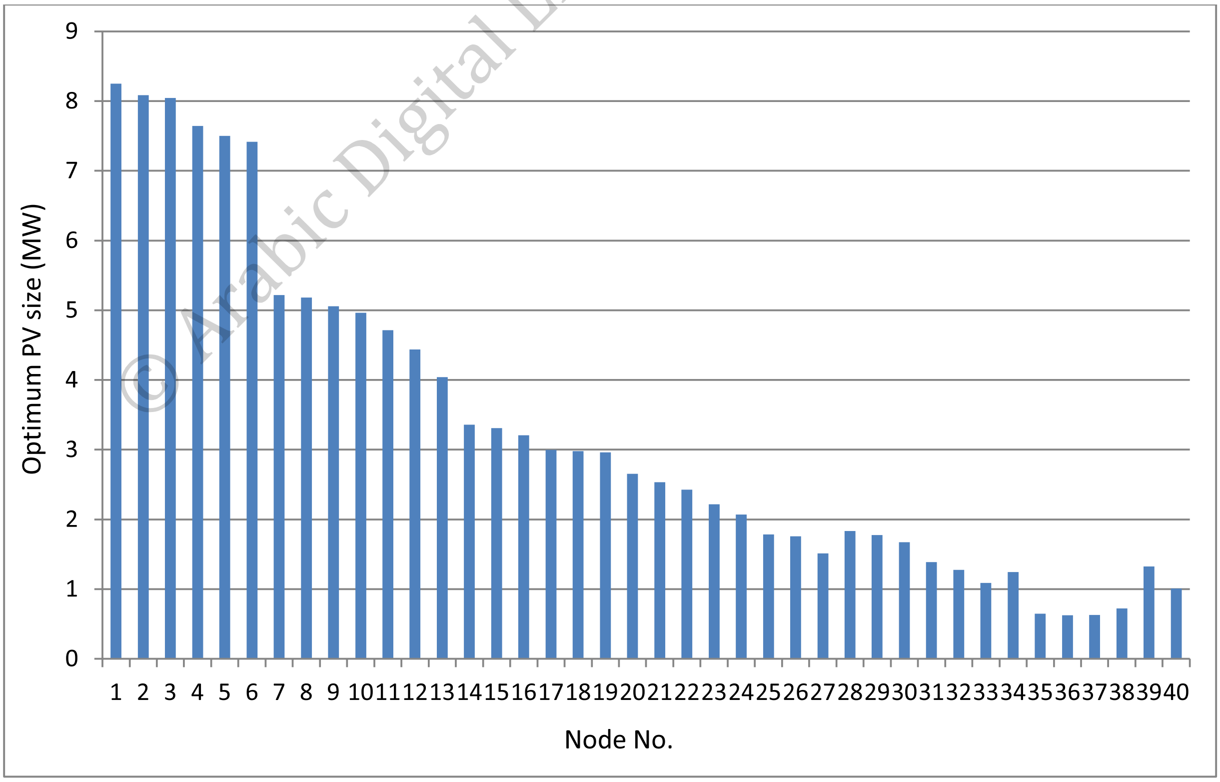


Figure 6.1: Optimum Size of PV system at various nodes for Ajloun Feeder

It is important to determine the location in which the total power losses are the minimum. Fig.6.2 shows the total power losses for the feeder system with optimum PV sizes obtained at various nodes of feeder. These results are good to identify the location that at which the total power losses are the minimum value.

In Ajloun feeder, the optimum location of PV is node 13, where the total power losses reduced to 220 KW, as depicted in Figure 6.2. The reduction in real power loss for this case is 38.2%. The second best location is node 18, where the total power losses are 225 KW. As it can be seen from results for studied system, the location and size of PV play an important role in losses reduction for distribution systems.

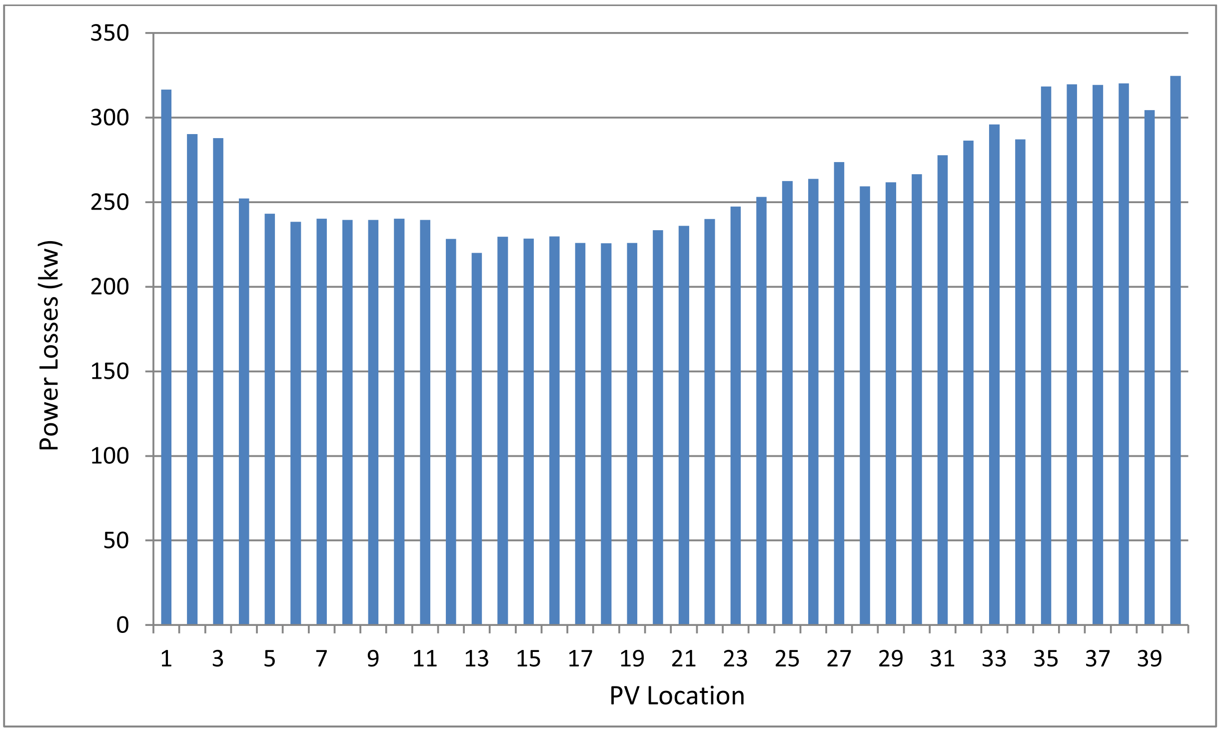


Figure 6.2 losses of Ajloun Feeder when PV with optimum size is located at different nodes

To achieve the optimum location, priority list for Ajloun feeder nodes according to power losses was established as shown in table 6.1. Also, the ranking for sensitive nodes for voltages was illustrated at table 6.3 according to power flow at normal case. Table 6.2 shows the voltage profile of system nodes before PV installation.

Table 6.1: Priority list of sensitive Ajloun feeder nodes to power losses

Rank	Node No.	Rank	Node No.
1	13	18	29
2	18	19	25
3	17, 19	20	26
4	12	21	30
5	15	22	27
6	14	23	31
7	16	24	32
8	20	25	34
9	21	26	3
10	6	27	2
11	8, 9, 11	28	33
12	7,10,22	29	39
13	5	30	1
14	23	31	35
15	4	32	36,37
16	24	33	38
17	28	34	40

Table 6.2: The voltage profile of the feeder nodes after load flow

Node ID	Node Name	V (p.u)	Node ID	Node Name	V (p.u)
1	00015331	0.982	21	00015407	0.932
2	00015333	0.977	22	00015423	0.931
3	00015335	0.977	23	00015427	0.931
4	00015337	0.971	24	00015430	0.93
5	00015339	0.969	25	00015432	0.93
6	13338	0.968	26	00015435	0.93
7	00015341	0.964	27	00015433	0.93
8	00015343	0.963	28	00015409	0.932
9	00015348	0.963	29	00015411	0.931
10	00015351	0.963	30	00015414	0.93
11	00015353	0.961	31	1596	0.931
12	00015358	0.954	32	00015393	0.935
13	00015367	0.946	33	00015396	0.935
14	00015369	0.944	34	00015402	0.935
15	00015377	0.943	35	00015387	0.935
16	00015379	0.942	36	00015390	0.935
17	00015382	0.936	37	00015388	0.935
18	00015384	0.935	38	00015374	0.944
19	00015398	0.935	39	00015359	0.954
20	00015400	0.934	40	1585	0.963

Table 6.3: The Priority list of sensitive Ajloun feeder nodes to voltage

Rank	Node No.	Voltage Value (p.u)
1	18,19,20,21,22,23,24,25,26,27,28,29, 30,31,32,33,34,35,36,37	0.930-0.935
2	17	0.936
3	13,14,15,16,38	0.942-0.947
4	12,39	0.954-0.959
5	7,8,9,10,11,40	0.960-0.965
6	4,5,6,	0.966-0.971
7	2,3	0.972-0.977
8	1	0.982

By comparing the two priority lists according to power losses and voltage profile, the best location for PV installation is found. The new priority list is shown in table 6.4. It shows that the optimum location to achieve lower power losses and not poor voltage profile is node 18 with optimum size 2.662 MW. Nodes 13 and 19 are the second one with optimum size 3.607 MW and 2.654 MW respectively.

Table 6.4: The result priority list for placement of PV system

Rank	Node No.
1	18
2	13,19
3	17
4	12,15
5	14,20
6	21
7	16
8	22
9	23
10	6,8,9,11
11	7,10,24
12	28
13	5,29
14	25
15	4,26
16	30
17	27
18	31
19	32
20	34
21	33
22	3,36,37,39
23	2
24	38
25	1
26	40

The annual cost of system losses for base case without connecting a PV system is 68,674 JD, but the annual cost of system losses for PV system with optimum size at optimum location is 43.362 JD. The reduction percent for annual losses is 36.9%.

CHAPTER Six

CONCLUSIONS

AND

FUTURE WORK

Ch.6 CONCLUSIONS AND FUTURE WORK

6 .1 ***Introduction***

This study has been focused on issues related to distribution systems with a different high penetration of PV generation: power flow, power losses, and feeder voltage profile where PV system is connected. The system response according to solar radiation and temperature variations are investigated. These results as a power flow study on IDECO grid aims to study the voltage stability of the system. Several conclusions will be mentioned according to simulation results and analysis.

6.2 ***Conclusions***

In this work, a large scale of grid connected PV was chosen to be an alternative energy source for conventional energy due to the convenient solar radiation incident on Jordan areas. Connecting a large scale of PV with power system has impacts on power system. One of these impacts discusses in this study is the power flow which results in voltage stability or instability.

As illustrated in the simulation and analysis, results conduct the following points:

The results show that the feeder power losses are slightly high and the feeder voltage profile curve is poor when the PV system is not connected to grid. When the PV system is connected into power grid, the power losses are reduced due to the reduction of the power flow from generator source, also the voltage profile at each node is improved due to the reduction of power losses in the feeder and the increase of power at each node.

The results show that the power losses are smaller and the voltage profile is better when amount of PV penetration is higher. But, at a high value of PV penetration, the power losses increases and the voltage profile becomes worse as a result of increasing of the PV system output to a level more than optimal value which leads to flow the power for far loads.

From the results, it is clear that the optimal location of the studied locations to reduce the total power losses and improve the voltage profile is varied with PV size. The optimum location is at location three at the end of the feeder when connecting 1MW and 2MW PV system as a result of load configuration at this location. At 1MW and 2 MW, the PV system will supply near loads without transferring output power for long distance. While connecting 3 MW PV system at the end of the feeder will lead to supply the near and far loads causing an increase in feeder power losses and less improvement in voltage profile. So, the optimal location at 3MW is location two at middle of the feeder due to supply the near loads by the PV generated power without transferring a valuable power for long distance. The worst location is location three at the end of the feeder while connecting three 3MW due to the long distance needed to supply the loads by the PV generated power.

The feeder power losses and voltage profile vary by solar radiation and panel temperature, which is due to the effect of the radiation and temperature on the value of the PV system output power, whether it is around the optimal value for enough to have more losses.

From the results, it is clear that the feeder power losses become lower when the solar radiation is higher when 1MW and 2MW PV system is connected to the feeder because the output power for all solar radiation values is still below the optimum size of PV system. While a 3 MW PV system is connected to the feeder, as the solar radiation increase, the output PV power increase until approximately reaches the value of the best of PV size. At solar radiation 1000 W/m^2 the power losses is the largest because the output power at this solar radiation exceeds the optimum size of PV system.

Also, from the results it is clear that the feeder power losses become higher when the panel temperature is higher (i.e. PV output is lower) when 1MW and 2MW PV system is connected to the feeder because the output power for all temperature values is still below the optimum size of PV system. While a 3 MW PV system is connected to the feeder, as the panel temperature increases, the output PV power decreases until it approximately reaches the value of the best of PV size (i.e. least losses). At all temperature values, the power losses increase because the output power at these temperature values is exceeded the optimum size of PV system.

It is obvious that for a certain case of PV generation level, we can't conclude the relation between the solar radiation or panel temperature and the feeder losses because the feeder losses are PV size and location dependent.

The power losses and voltage profile at each node are varied according to the PV size and location where PV system is connected. The power losses are increased not decreased and the voltage is not improved when the PV generation capacity is higher than the optimum capacity. So, the optimum size and location could be optimized to reduce the power losses to the lowest value and to achieve the optimum improvement of the feeder voltage. In this study, the optimum location for Ajloun feeder of IDECO system is at node 00015384 namely 18 with optimum size 2.662 MW.

These results help to determine the maximum PV penetration and location that improve the voltage profile.

6.3 ***Future Work***

1. Higher large scale PV system can be connected to a high voltage transmission lines to investigate the impacts on the power system.

2. Transient analysis of PV generation as sudden tripping of PV generation and actual fluctuating in solar radiation can be studied.

3. More than one generation source can be implemented into power system.

4. Voltage control techniques can be used to mitigate the fluctuation in voltage caused by PV generation.

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الملخـــــــــــــص

الزعارير، خالد أحمد. تحليل الاستقرارية لنظام توزيع كهربائي مغذى بالخلايا الضوئية. رسالة ماجستير قسم هندسة القوى الكهربائية، كلية الحجاوي للهندسة التكنولوجية، جامعة اليرموك. 2012 (المشرف: د. عبدالغني عثامنة)

أوجدت الطاقة المتجددة اهتماما ملحوظا خلال السنوات الاخيرة مع زيادة التركيز على حماية البيئة العامة لانتاج طاقة طبيعية خالية من التلوث. أصبح الأردن واحدا من الدول التي تنظر الى الاهتمام بتوليد الطاقة المتجددة المربوطة مع نظام توزيع كهربائي. تملك مصادر الطاقة المتجددة كالشمسية، الرياح والطاقة الحيوية تأثيرا كبيرا للاستخدام الدائم في أنظمة التوليد بالمقارنة مع الانتاج من الوقود الأحفوري. عند التحدث عن الطاقة الشمسية كنظام بديل للطاقة فإن الطاقة الشمسية نظيفة، خالية من التلوث، ولا تنفذ مع مرور الوقت.

التسويق الأولي للطاقة الشمسية كان أكثره للخلايا الشمسة المفصولة عن الشبكة الكهربائية. هذه الايام التسويق العالمي هو الخلايا الشمسية الموصولة مع الشبكة حيث الطاقة تغذى من و إلى الشبكة الكهربائية. الخلايا الشمسية الموصولة مع الشبكة تغطي مجال واسع من مستويات الطاقة من أنظمة الطور أحادي التغذية الى الطور ثلاثي التغذية. تعرض الدراسات الحالية زيادة في سعة الطاقة الشمسية المركبة في العالم لذلك تم التوجه لتطبيق الخلايا الشمسية ذات القدرات المرتفعة.

الخلايا الشمسية ذات القدرات المرتفعة تؤثر على استقرارية وتشغيل النظام الكهربائي. من هذا المنطلق فإن الاهتمام في هذا العمل لكي ندرس تأثير أنظمة الخلايا الشمسة على سلوك نظام التوزيع الكهربائي.

تمت المحاكاة وتحليل الانظمة في شركه كهرباء محافظة اربد الأردنية وهي شركة مسؤولة عن توزيع الطاقة الكهربائية في شمال المملكة الأردنية الهاشمية.

كلا من برامج CYME و MATLAB تم استخدامها لتقصي هذه النتائج. بعد ذلك،أظهرت النتائج ان الخلايا الشمسية المربوطة مع نظام التوزيع الأردني لها تأثير على تدفق الطاقة وفولتية نظام التوزيع حيث تمت المقارنة ما بين أحجام مختلفة للخلايا الشمسية.على الأكثر، تم تحديد المكان الأمثل لربط الخلايا الشمسية على المغذي حيث تم الأخذ بعين الإعتبار قيم إشعاعية ودرجات حرارة مختلفة.

في النهاية، تم تحديد الحجم والمكان المناسب لنظام الخلايا الشمسية على مغذي التوزيع التابع للنظام الكهربائي الأردني.