Arab Academy for Science, Technology and Maritime Transport

College of Engineering and Technology

Electrical and Computer Control Department

M. Sc. Thesis

Investigating the Effect of Adding a PV System to the Reliability of a Large Power System

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January – 2012

DECLARATION

I certify that all the material in this thesis that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this thesis reflect my own personal views, and are not necessarily endorsed by the University.

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We certify that we have read the present work and that in our opinion it is fully adequate in scope and quality as a thesis towards the partial fulfillment of the Master's Degree requirements in

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ACKNOWLEDGMENT

I owe my deepest gratitude to Prof. M. Magdy Eteiba and Dr Eman Beshr, whom undertook the supervision of this thesis. Prof. Magdy was abundantly helpful and offered invaluable assistance, support and guidance. I would like to thank them for sharing with me their experience, giving me plenty of their time and continuously guiding me through my research. Without them, this thesis would have not reach completion.

I would also like to show my gratitude to Prof. Yasser Galal, head of Electrical Department, for his kind concern and advice during my undergraduate and postgraduate studies. As I would like to thank all my department's colleagues for their care and support, especially Dr Noha Youssry, Eng. Salwa Youssry and Eng. Hammam Abdelaal for the hand of help they continuously offered.

I am very grateful to Dr Jihan El Shazly, Eng. Ahmed Madani, Eng. Ayman Esmat and Eng. Hussam Abdel Hasib for their time, support and help. They have added a lot to the completion of this thesis.

I am indebted to my sweetest friends; Reem Mansour, Basma Bargal, Bassant Osama and Madiha El Refai, for their help, encouragement and support. Their continuous care had always inspired and motivated me.

Finally, I would like to express my love and gratitude to my beloved family; my parents, brothers and their wives, for their understanding and endless love, through the duration of my studies. Their encouragement and motivation was always the reason behind all my achievements.

ABSTRACT

As the cost of fuel associated with conventional energy sources keeps on escalating and for its negative environmental effect, the use of renewable energy in electrical power generation increased effectively. Solar energy is considered to be one of main types of renewable energy commonly used nowadays. For the past two decades, photovoltaic solar energy (PV) has experienced a remarkable growth in its widespread applications, particularly those connected to power systems (grid connected PV). Photovoltaic plants are expected to affect power system reliability in a different manner than conventional technology systems. As power generation plants using solar energy are integrated into existing power systems, it becomes essential to evaluate the reliability of these plants and assess the effects that they will have on the overall system reliability.

This thesis introduces a novel PV simulation model which is based only on datasheet values. The model estimates the electrical power output with respect to changes in two environmental parameters; temperature and solar radiation. Further modifications were made on the PV model to be applicable for reliability studies. It was implemented on Matlab® software package to accommodate any location in the world, but was addressed to two selected locations in Egypt; Hurghada and Cairo. The PV model was connected to a large power system; the Unified Electrical Network of Egypt (UENE). In addition, conventional generators of the UENE were modelled using state duration approach. Besides, actual load data was taken from the national grid. Reliability studies were carried out through three indices; LOLE, LOEE and LOLF to simulate the impact of adding a 140MW PV plant to the grid. Parameters were varied to investigate the impact of PV integration in different cases. Monte Carlo Simulation (MCS) technique is used for the convergence of these results after a long time of simulation.

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LIST OF ACRONYMS/ABBREVIATIONS

ACRONYM	**Definition of Acronym**
A	Ideality Factor
AST	Apparent Solar Time
E_g	Band Gap Energy for Semiconductor
ET	Equation of Time
FOR	Forced Outage Rate
G	Solar radiation in kW/m2
G	Solar Radiation
G_n	Measured Beam Radiation
G_{sc}	Solar Constant (1366 W/m^2)
HLI	Hierarchical Level 1
HLII	Hierarchical Level 2
HLIII	Hierarchical Level 3
I_D	Diode Current
I_{MPP}	Current at Maximum Power Point
I_{OR}	Reverse Saturated Current
I_{Ph}	Light Generated Photo-Current
I_{PV}	PV Module Output Current
I_{SC}	Short Circuit Current

I_{SH}	Shunt Current
K	Boltzmann's Constant
LL	Local Latitude
LOEE	Loss of Expected Energy
LOLE	Loss of Load Expectation
LOLF	Loss of Load Frequency
LST	Local Standard Time
MTTF	Mean Time to Fail
MTTR	Mean Time to Repair
MW	Mega Watt
n	Number of Cells in a Module
N	Number of Simulation Years
P_{MPP}	Power at Maximum Power Point
P_{PV}	PV Total Power From one Module
P_{PVA}	PV Total Power From an Array
PV	Photovoltaic
Q	Electron Charge
R_P	Parallel Resistance same as (R_{sh})
R_s	Series Resistance
R_{sh}	Shunt Resistance same as (R_P)
SM	Standard Meridian

T_a	Ambient Temperture in Kelvin
T_{OFF}	Off Time Duration
T_{ON}	Rated Power Duration
T_R	Reference Temperature in Kelvin
V_{MPP}	Voltage at Maximum Power Point
V_{OC}	Open Circuit Voltage
V_{PV}	PV Module Output Voltage
V_t	Thermal Voltage
δ	Declination of the sun in degrees
λ	Unit failure rate
Φ	Latitude of the Location in degrees
ω	Solar hour angle in degrees
μ	Solar Constant (1366 W/m^2)

Chapter One

1 INTRODUCTION

1.1 General

This chapter presents a thesis overview, emphasizing the motivations behind the research and the objectives required to be achieved. It also outlines a brief description of each chapter.

1.2 Motivation

The demand on electrical energy is rapidly increasing as a result of the population growth and industrialization projects. An increase in electrical generation is needed to supply this demand. Previously, the electrical utilities generated electricity using conventional generators that mainly used fossil fuels. However, this has a negative environmental impact as it accounts for a significant portion of pollution and greenhouse gas emissions, which are considered the main reason behind the global warming. In addition, conventional generators also have potential problems in regard to sustainability due to the limited reserves of coal, oil, and natural gas. Recently, the world's trend has been directed towards renewable energies. Renewable energy provides clean and safe electrical power. There are different types of renewable energy used to generate power, one of those is Photovoltaic (PV) power, which is a very promising renewable energy source throughout the world.

Egypt is one of the countries suffering from high population and electrical demand. Figure 1-1 illustrates an increase in demand between 2005 and 2010, from 17300MW to 22750MW accounting for a 31.5% increase. On the other hand, the total installed capacity in Egypt up until 2010 was 24, 726 MW. As illustrated in figure 1-2, the installed capacity is divided into; Gas 11.5%, Steam 46.3%, Hydro 11.3%, Combined Cycle 28.9% and Wind 2% [1].

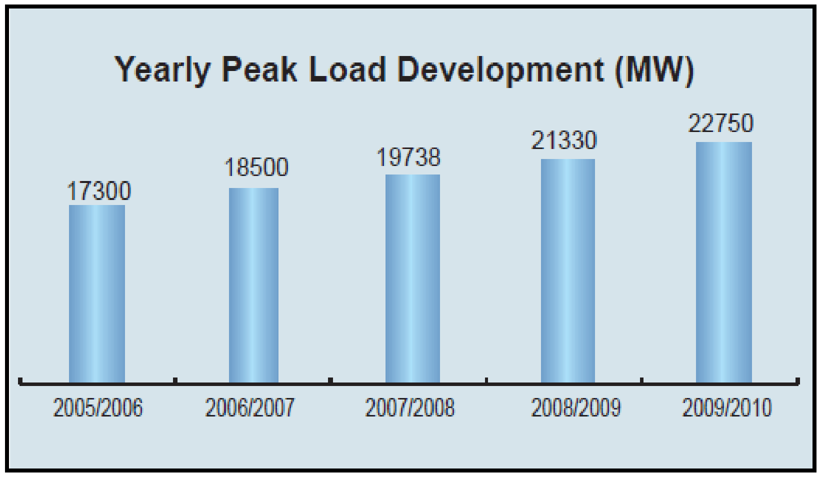


Figure 1-1: Annual Electrical Peak Load Development.

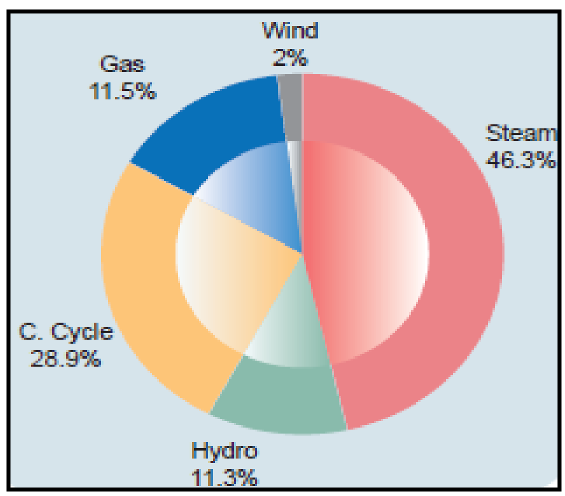


Figure 1-2: Division of Types of Generations for the Total Installed Capacity in Egypt, 2010.

Early during 2011, an extra 140MW was connected to the Unified Electrical Network of Egypt through an integrated solar combined cycle power plant, including a solar share of 20 MW [1]. The project's total cost is 340 Million Dollar and it is one of 3 similar projects that are being implemented in Africa (Morocco, Algeria, Egypt), which mainly depends on integrating solar field with combined cycle. The project is based on parabolic trough technology integrated with combined cycle power plant using natural gas as a fuel as shown in figure 1-3. Kuraymat, the project's site, is located nearly 90 km South Cairo and has been selected for four main reasons:

- High intensity direct solar radiation that reaches 2400 kWh /m^2 / year.
- An Extended unified power grid and expanded natural gas pipelines.

- Located near to the sources of water (the River Nile).
- An uninhabited flat desert land.

Figure 1-3: The first Solar Thermal Plant in Kurymat.

Solar projects are considered one of the main aspects to increase the contribution of renewable energies in Egypt. Two projects are to be established in the coming up five years (2012- 2017);

- Solar thermal electricity generation plants, using Concentrator Solar Power (CSP) with total capacity of 100 MW in Kom Ombo city.
- Photovoltaic plants with total capacity of 20 MW.

The use of photovoltaic (PV) systems for electricity generation started in the seventies of the 20th Century and is currently growing rapidly worldwide. It is expected that the global cumulative PV capacity will reach 200 GW by the year 2020 and 800 GW by the year 2030, based on the European Photovoltaic Industry Association (EPIA) [2], as shown in Figure 1-4. Photovoltaic system has many advantages that promote it to be one of the most commonly used renewable energies. It requires a short duration of time to design, install and start up a new PV plant, and its power output matches very well with peak load demands. In addition, PV is highly mobile and portable because of its light weight. It also requires little maintenance for being static structure with no moving parts.

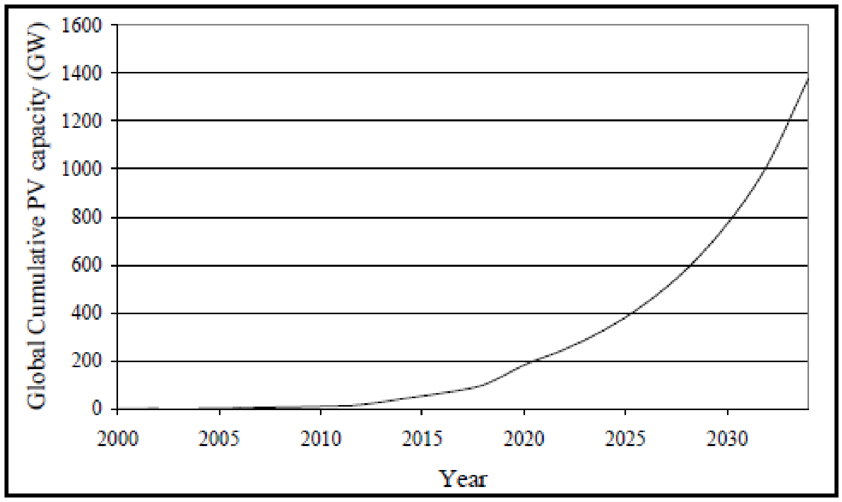


Figure 1-4: Expected global cumulative PV capacity based on EPIA data [2].

1.3 Research Objectives

Since PV plants are being world widely used and their share in the total electrical generation is increasing, it is essential to study their effect on the power system reliability. Power system reliability evaluation is important for studying the current system to identify weak points in the system, determining what enforcement is needed to meet future demand and planning for new reliable power system, i.e., network expansion. Reliability studies are vital to avoid economic and social losses resulting from power outages.

This thesis investigates the reliability impact of adding a photovoltaic system to a large power system. The PV system is virtually implemented in Hurghada to test its performance, then in Cairo. Reliability studies are carried out to evaluate the performance of the PV system during its integration to the Unified Electrical Network of Egypt. Different parameters were varied to study the reliability performance in different cases.

The objectives of this thesis are accomplished through:

- Proposing a novel PV simulation model that estimates the output PV power, suitable to be used in reliability studies. The model is based only on datasheet values and derived mathematical equations.

- Modeling conventional units of a large electrical network; the Unified Electrical Network of Egypt. This is done using state duration approach and actual data from the grid. In addition, actual data of load demand is also taken from the grid to be simulated.

- Reliability studies are carried out to compare the electrical power system's performance before and after the PV plant integration during different cases.

1.4 Thesis Outline

To achieve the aforementioned objectives, the thesis is organized into six chapters:

- **Chapter 1:**

This chapter introduces the main aim, objectives and motives of this thesis and its outlines.

- **Chapter 2:**

A brief literature review is presented on various aspects of previous research work. Two areas were of main interest; reliability analysis and solar energy, particularly grid connected PV systems.

- **Chapter 3:**

This chapter gives a brief background about solar energy and emphasises on the photovoltaic solar energy. A novel simulated PV model is discussed in this chapter, proposing the algorithm used to simulate a PV model suitable for reliability studies with the aid of Matlab® software package.

- **Chapter 4:**

In this chapter, the Unified Electrical Network of Egypt is modelled using Matlab® software package for reliability analysis. This chapter uses the model driven from chapters 3 along with the model derived in this chapter, to study reliability analysis.

- **Chapter 5:**

This chapter presents all results achieved. It starts off with results to verify the PV model of chapter 3 and the effect of varying environmental parameters on the model. Moreover, a comparison between the two locations for the PV implementation is simulated, along with the PV power output in each site. The results of the reliability analysis are simulated in four different cases, showing the impact of adding the PV to the national grid.

- **Chapter 6:**

Finally, the summary and conclusion of the thesis are presented. This chapter outlines the contributions of the presented research and suggests future work that could be carried on.

Chapter Two

2 LITERATURE SURVEY

2.1 Introduction

This chapter presents previous work that had been reported in the two areas; Photovoltaic Solar Energy and Reliability Studies. The scope of this chapter is to highlight the problems and deficiencies previously encountered in simulated studies, in order to improve them. Different PV models and applications are discussed. In addition, a review on studies considering PV modeling and reliability studies are presented.

2.2 Photovoltaic Solar Energy

2.2.1 Modelling Photovoltaic Systems

There are three main models usually used to study a PV cell/module; one-diode model, two-diode model and empirical model. Figures 2-1, 2-2 and 2-3 illustrate the three models respectively [3].

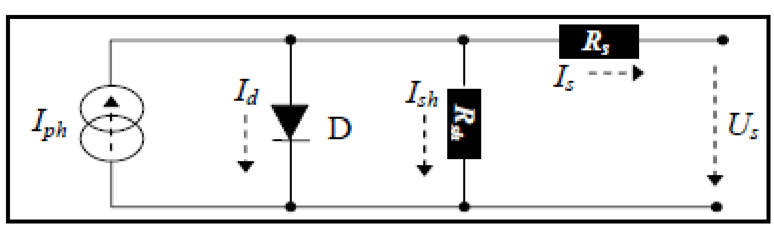


Figure 2-1: One-Diode PV Model.

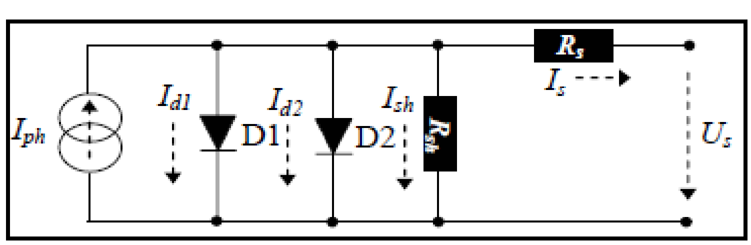


Figure 2-2: Two-Diode PV Model.

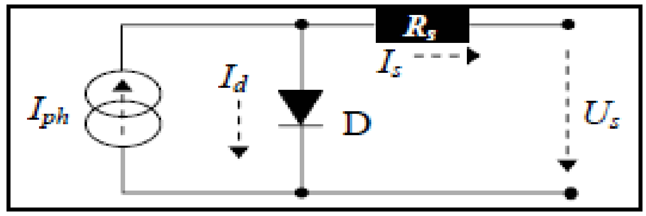


Figure 2-3: Empirical PV Model.

Empirical PV cell model is widely used in modelling due to its simplicity and limited number of parameters, however it is not considered the most accurate. Whereas, the two-diode model is very accurate, but not frequently used, for its complexity. It is mainly suitable for studies that require detailed cell information. Most researches use one-diode model as it considers all the needed parameters to accurately model a PV that could used to identify the impacts of PV systems on the electric network. Four main parameters are usually what differ between models; shunt resistance (R_{sh}), series resistance (R_s), ideality factor (A) and the reversed saturated current (I_{OR}).

Several researches used the empirical model to facilitate the modelling procedure. References [3-7] all used the empirical model and applied it on Matlab®, by eliminating the shunt resistance. The accuracy of each differed due to the variation in parameter calculations. [4,5,6] calculated the R_s by using dV/dI at Voc point on the I-V curve, whereas for the ideality factor was kept as a random number between (1-2) that set to achieve the best curve match. In [7] two models were simulated; the first model is kept to adjust A for curve best fitting. It used temperature and solar radiation correction values for voltage and current, in a similar manner to [8]. The second model calculated A and R_s and used temperature dependence of voltage. By comparing the simulation results from both with experimental results, it was concluded that the second model was the most reliable one.

[9-14] proposed a PV model using single diode based on datasheet values. In [9, 10] all parameters were modelled into a series of equations that were solved simultaneously. The obtained values have been used in the implemented model which exhibited a very good agreement with all the specifications given in the product datasheet. The algorithm was accurate but very complicated. Whereas in [11], an accurate model of I_{OR} was presented. However, Rs,Rp and A are assigned values for which the model gives least error. A novel method for the

determination of Rs is presented in [13]. The results was compared to actual values and showed to be relatively similar.

In [15-19] Matlab®/Simulink was used to accommodate the implemented PV model. The author of [15] developed a dynamic PV model that simulated up to 21% more energy than static model when using actual weather data. Static PV models, are those of constant temperature and solar radiation inputs, whereas dynamic PV models are those with a varying temperature or solar radiation input. Whereas [16] implemented an accurate one-diode model, but for a constant ideality factor and R_s. In addition, [17] carried out a study on PV cells, modules and array with experimental verification. A comprehensive behavioural study is performed under varying conditions of solar radiation, temperature, varying diode model parameters, series and shunt resistance.

On the other hand, [18] is based on two-diode model, although greater accuracy can be achieved using this model, yet it requires the computation of more parameters than the other two models. However, this paper proposed an improved two-diode model with reduced number of parameters. The Rs and Rp are estimated by an efficient iteration method.

There are other methods used to identify the photovoltaic model parameters, such as Robust Linear Regression Methods [20] or using Fuzzy Regression Model [21]. In [22], the author used Artificial Neural Networks (ANN) technique to model an empirical PV model on the Matlab®. However, the model was more accurate than previous proposed models for the extra considerations taken, such as; dividing the open circuit voltage on number of cells and calculating the ideality factor and R_s through mathematical equations. Yet, the R_s equations are considered complicated.

There are other environmental parameter that affect the power output of PV; shading and dust. The author of [23] studied the influence of long-term dust accumulation on the surface of photovoltaic module. Besides, an investigation was carried out to determine the acceptable suitable interval between each two successive cleaning processes. In addition, a comparison was carried out between two cleaning methods; dry and wet. In [24] a simulation of uniform shading is presented. A comparison between results of a two-diode model simulation and experimental results was carried out and were of approximately the same values. [25] Also modelled the performance of a PV array taking in considerations temperature, solar radiation, shading and the array's configuration. Results showed the impact of variation of parameters on I-V and P-V characteristic curves of the PV.

[26] studied how to optimise the energy yields from photovoltaic panels and proved that MPPT is of vital importance in ensuring optimal performance of any PV array.

2.2.2 Grid-Connected PV applications

PV applications are divided into stand alone and grid-connected systems. References [27, 28] are examples of stand alone systems, where [27] provides a method to estimate daily solar radiation used for solar home systems. Where in [28] a new modified configuration for a stand alone PV system is presented to be used to electrify a remote area household load in Egypt.

Many publications are available on grid connected applications and modelling [29-38]. Part of those researches are conducted to certain countries such as in [29] which presented a computer simulation program of a single phase grid connected PV system using Matlab/Simulink in order to monitor the performance of each unit of the system during a sunny day and another cloudy day at Kharaga Oasis Site. The model used hourly data of load demand, solar radiation and temperature. A mathematical model of all system components was introduced through which the dynamic behaviour of each sub-system was investigated. A similar approach was studied in Thailand but experimentally in [35]. Besides, [33] presents a case study of grid connected PV in Zurich, Switzerland. Moreover, a model to evaluate the marginal price of grid connected PV plant in China in [37] and suggestions were also proposed for facilitating the improvement of grid-connect PV. Other grid-connection applications are extended in the use of distributed generation application [39].

Grid connected PV systems has many advantages, however it faces a couple of technical and potential problems. Reference [31] presents a review on the importance of the grid connected PV system regarding intermittent nature of renewable generation and the characterization of PV generation. One of the technical problems discussed, was the satisfaction of the reliability performance from the utility grid.

2.2.3 PV studies for Egypt

Many studies were carried out for the integration of PV in Egypt [40-44], one of which was mentioned earlier [28]. [42] Discusses different PV activities and projects in Egypt and emphasis on community field projects, utilizing PV for different applications. A research was carried out finding the available wind and PV energy resources in Egypt [40]. Six locations in Egypt were examined to accommodate a PV system, from which Hurghada was picked to be the best location. In [41] a simulation model for predicting the performance of PV and wind was implemented on Matlab/Simulink. However, the model had assigned values for many parameters, such as A, R_s and R_p of the one-diode model in figure 2-1. In addition, the same author extended the research into a case study for Sinai in Egypt [43]. The paper presents a design of a model to serve a safari village in Sinai. As all PV models require solar radiation input, [44] presents an empirical method for estimating the solar radiation in Egypt.

2.3 <u>Reliability Analysis</u>

Generation system reliability is an important aspect in the planning for future system capacity expansion. It provides a measurement of reliability or adequacy to make sure that the total generation system capacity is sufficient to provide adequate electricity when needed. However, the research on reliability analysis for power systems with PV integrations is very limited.

Reference [45] presents an innovative method for assessment of generation system reliability using genetic algorithm (GA). The GA method was used as a state sampling tool for evaluating a composite generation-transmission (HLII) power system through adequacy indices. Whereas, [46] also calculates the same indices for a composite generation and transmission system with a single or multiple wind/solar sites. Both authors used state duration approach to model conventional units within the power system. Besides, [47] the research is conducted to (HLII) through the calculations of LOLE (Loss of Load Expectation), LOLF (Loss of Load Frequency), LOEE (Loss of Energy Expectation) using Monte Carlo Simulation (MCS).

Reference [48] presents a method of assessing the reliability of large-scale grid-connected PV system. Fault tree analysis (FTA) technique was used to demonstrate the interdependencies between all the components belonging to the overall PV system. Besides, [49] study showed that 69% of the unscheduled maintenance of a PV system is due to the inverter, 21% due to the system and only 10% due to the PV.

In [50] Reliability analysis is carried out through two indices; LOLE (Loss of Load Expectation) and LOEE (Loss of Energy Expectation) for a small autonomous power system. Whereas, [51] presents the hourly solar radiation and standard deviation as inputs to simulate the solar radiation over a year. Monte Carlo Simulation (MCS) technique is applied and Matlab program is developed for reliability analysis of small isolated PV system. In addition, [52] employed a sequential Monte Carlo Simulation approach to develop a comprehensive technique for generating capacity adequacy evaluation of power system containing both wind and solar energy. The PV and Wind powers were simulated using software. Reliability was examined in terms of LOLE, LOEE and LOLF for different cases. On the other hand, [53] preformed reliability analysis for a power system containing wind energy using analytical methods that represent the system by mathematical models, and then used direct analytical solutions to evaluate reliability indices from the model instead of using MCS.

The survey showed a good contribution in modelling PV using different techniques and models. However, reliability studies on grid connected PV is very limited. This thesis aims to propose a novel accurate PV model suitable for reliability analysis. Reliability studies will be carried on to investigate the impact of connecting PV to the grid.

Chapter Three

3 SOLAR ENERGY AND MODELING OF PHOTOVOLTAIC SYSTEM

3.1 Introduction

There are two types of energy sources; renewable and non-renewable energy, as shown in figure 3-1. Renewable energy sources are those that can be used over and over without running out of its supply. This includes solar energy from the sun, wind energy, geothermal energy from inside the earth, biomass from plants, and ocean energy from water. On the other hand, non-renewable sources are those that could be used up and cannot be recreated in a short period of time. This includes the fossil fuels; oil, natural gas, and coal. They are called fossil fuels because they were formed over millions of years by the action of heat from the Earth's core, pressure from rock and soil on the remains of dead plants and animals.

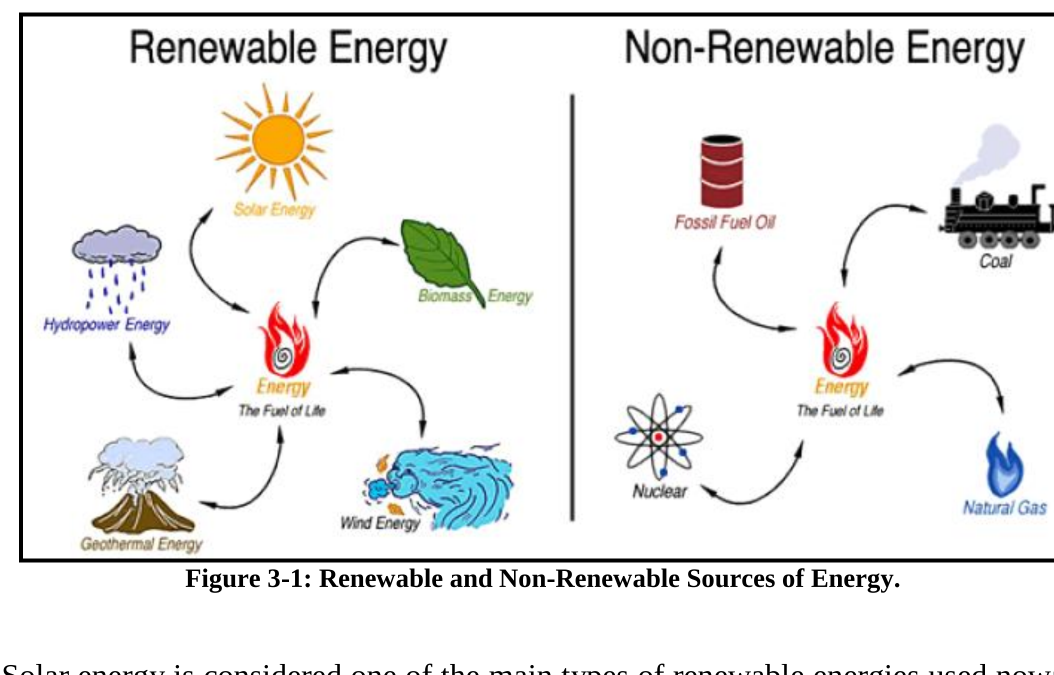


Figure 3-1: Renewable and Non-Renewable Sources of Energy.

Solar energy is considered one of the main types of renewable energies used nowadays. It is used in a wide variety of applications with different capacity values. This chapter describes the types of solar energy and focuses on one of them; the photovoltaic (PV) solar energy. PV system components are described and the impact of environmental parameters is discussed and modeled using mathematical equations. A flow chart is obtained to implement a PV model with the aid of Matlab® software package.

3.2 Solar Energy

Solar energy is energy from the sun that can be used as a source of electricity generation. It is considered to be the only source of electrical generation without any moving parts, noise and emissions. There are two types of solar energy systems; solar thermal and photovoltaic as illustrated in figure 3-2.

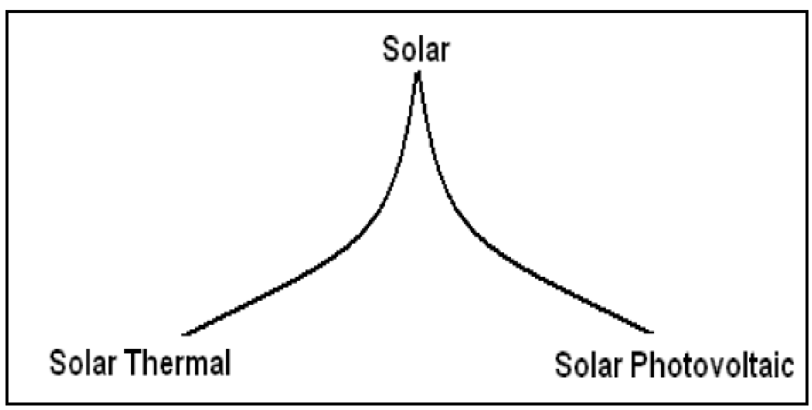


Figure 3-2: Types of Solar Energy

3.2.1 Solar Thermal System

This works on the technology of generating electrical power using solar thermal energy. It collects the thermal energy in solar radiation by concentrators and uses it in low temperature applications, such as water and space heating for commercial and residential buildings, or in high temperature application as that of the steam-turbine-driven electrical generator, as in figure 3-3. There are three alternative configurations of the concentrators, shown in figure 3-4; parabolic trough, central receiver and parabolic dish [54].

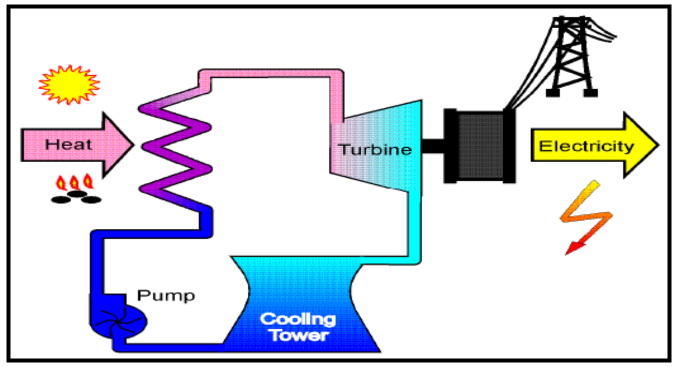


Figure 3-3:Solar Energy used for Steam-Turbine-Driven Electrical Generator.

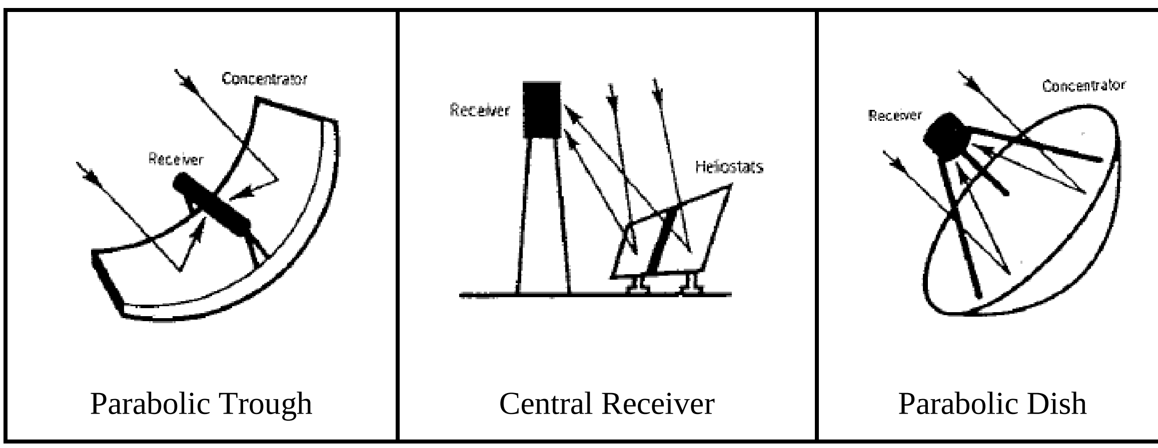


Figure 3-4: Alternative thermal energy collection technologies.

3.2.2 Photovoltaic Solar Energy

Another way to generate electricity from solar energy is to use photovoltaic (PV) cells, which convert light energy directly into electricity. Since the source of light is usually the sun, they are called solar cells. The word photovoltaic comes from “photo” meaning light and “voltaic” which refers to producing electricity. Thus, the photovoltaic process is “producing electricity directly from sunlight” [55].

PV power plants are considered better than thermal power plants for several reasons. One of those reasons is operating in a cloudy day. The global solar irradiance consists of direct and diffuse irradiance, as shown in figure 3-5. When skies are overcast, only diffuse irradiance is available. PV systems can convert the diffuse irradiance for power generation, while solar thermal power plants can only use direct irradiance. Another reason is that the PV plants' capacity is of a higher range than solar thermal power plants. In addition, PV power generation provide clean, safe and reliable electricity generation. Thus, this research is based on PV power generation.

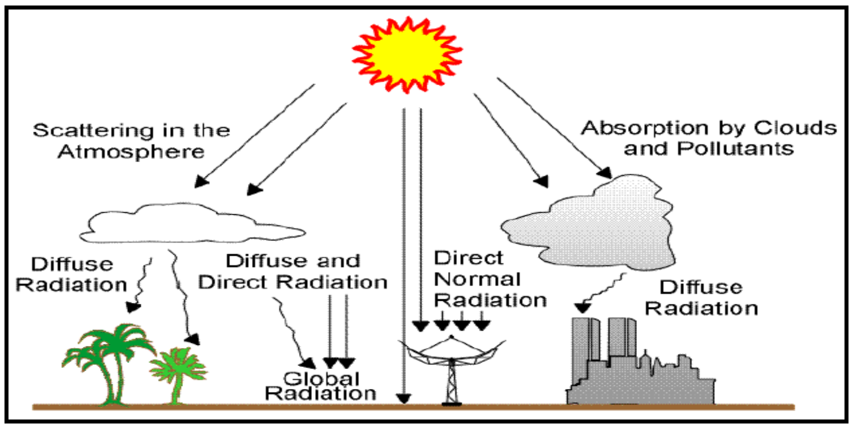


Figure 3-5:Division of Global Solar Radiation.

3.3 PV Systems

There are large scale applications of PV power generation. They are classified into two groups; stand alone PV system and grid-connected PV system. Stand alone PV systems are usually implemented in remote areas or for example on the rooftops of houses. Whereas, Grid connected PV systems are utility-interactive systems that are connected to the power line. Storage could be added to both types of solar systems. In this research, the performance of a grid-connected PV system is studied.

3.3.1 Components of Grid-Connected PV System

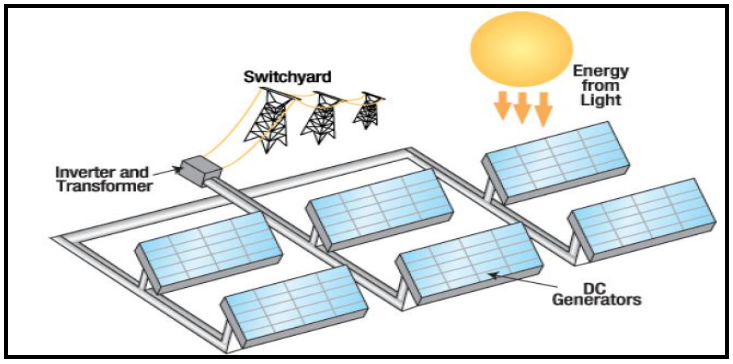


Figure3-6: Grid-connected PV system

Figure 3-6 shows the main components of grid-connected PV system. There are PV arrays that absorb the light energy from the sun and convert it into electrical energy. The PV array consists of a number of parallel strings that are made of several series module of series PV cells, as shown in figure 3-7. The PV array generates DC power that is converted into AC power through an inverter.

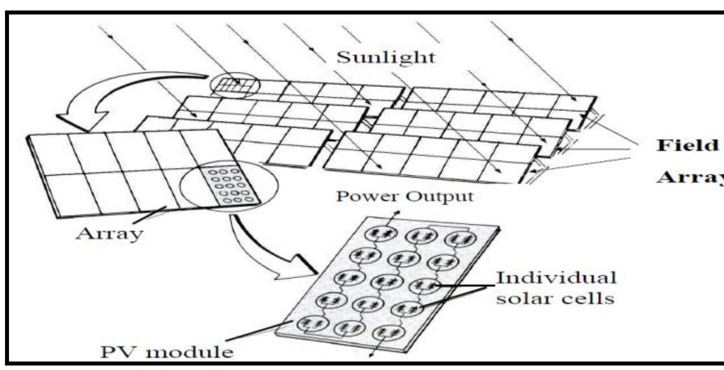


Figure 3-7: PV Cells, Modules and Arrays.

Inverters used in grid connection usually include maximum power point tracking system. The position of the maximum power points on the PV generator depends strongly on the solar radiation and the cells temperature. It is used to adjust the actual operating voltage and current of the PV generator so that the actual power approaches the optimum value as closely as possible. Operation of the PV generator at its MPP involves matching the impedance of the load to that of the generator. If the inverter does not include a MPP tracking system, an electronic device, normally a power conditioning unit, capable of performing the function of a MPPT has to be connected between PV generator and the load. A transformer is optionally added to the inverter to step up the voltage before the power is fed into the grid, in order to decrease power losses. Figure 3-8 illustrates two different connections usually used for the inverter. Individual inverters may be used for each string in an array as shown in (a), or another choice is to incorporate a large central inverter system that converts the total DC power as in (b) [56].

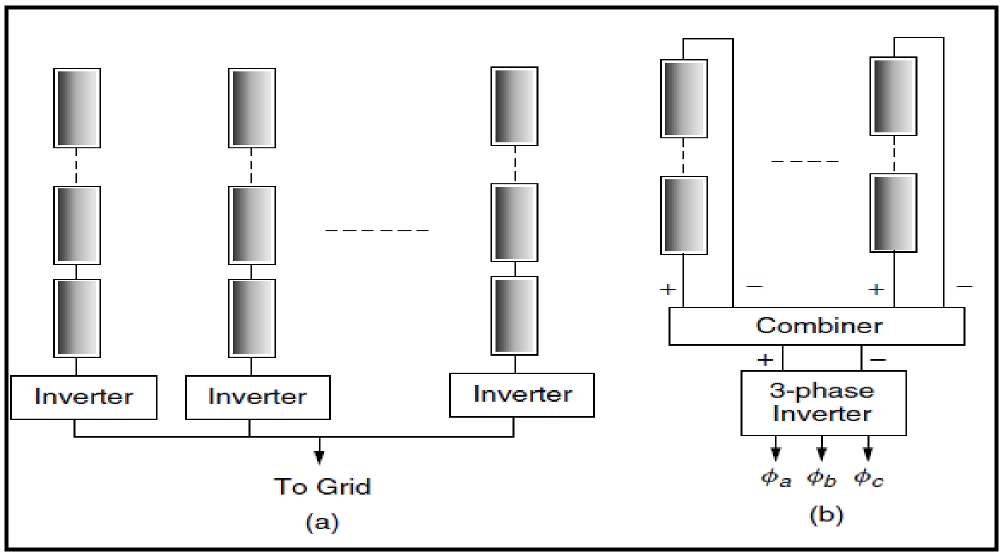


Figure 3-8: Different Inverter Connections to the Grid

3.3.2 PV Cell Technology

Photovoltaic cells convert solar radiation directly into DC electrical energy. The basic material for almost all the photovoltaic cells existing in the market, which is high purified silicon (Si)There are several types of PV cells, three of the most commonly used and found in the market are Mono-Crystalline, Poly-Crystalline and Thin Film (amorphous silicon) PV cells (data sheet for each available in appendix A,B and C respectively). Table 3-1 illustrates a comparison between different PV cell types, each of which has advantages over the other. Mono-Crystalline PV cell is made of a slice of crystal that makes it smooth and rigid. It is considered the most efficient and the most expensive to produce. On the other hand, Poly-Crystalline PV cell consists of a large number of crystals that gives a speckled reflective appearance. It is slightly less efficient compared to the Mono-Crystalline PV cell. As for the Thin Film PV cell, it is manufactured by placing a thin film of amorphous (non crystalline). It has the least efficiency as its output power decreases over time; however, it is considered the cheapest.

The Mono-Crystalline technology is commonly used as a reference, or baseline, for the solar power generation technology. In a typical crystalline cell, the bulk of the material is silicon, doped with a small quantity of boron to give it a positive or p-type character. A thin layer on the front of the cell is doped with phosphorous to give it a negative or n-type character. The interface between these two layers produces an electric field and forms the so called a “cell junction”. When the cell is exposed to sunlight, a certain percentage of the incoming photons are absorbed in the region of the junction, freeing electrons in the silicon crystal. If the photons have enough energy, the electrons will be able to overcome the electric field at the junction and are free to move through the silicon and into an external circuit. The direction of the electrical current is opposite to its direction if the device operates as a diode [57].

3.3.3 PV Cell Characteristics

The performance characteristics of a photovoltaic module depend on its basic materials, manufacturing technology and operating conditions. PV cells are described by their characteristic curves; Current (I) -Voltage (V) curve and Power (P) – Voltage curve as shown in figure 3-9. On the I-V curve, three points in these curves are of particular interest; short circuit current (Isc) which is corresponding to zero voltage, open circuit voltage (Voc) corresponding to zero current and the knee-point on the I-V curve is the maximum power point (MPP), for which the corresponding current (IMPP) and voltage (VMPP) values produce the maximum power value that could be obtained by the PV cell. The maximum power could be obtained from the P-V curve at maximum power point (PMPP) corresponding to (VMPP).

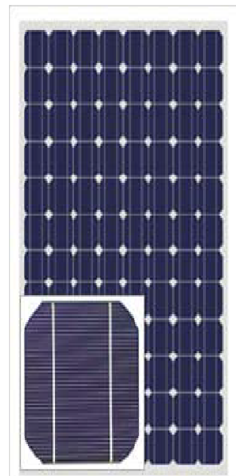
	Crystalline Silicon	Thin Film
Picture		
Module types and module efficiency	• Mono-crystalline Silicon (15-18%) • Poly-crystalline Silicon (13-16%)	• Amorphous Silicon (5-7%) • Copper Indium Diselenide (CIS) (9-11%) • Cadmium Telluride (CdTe) (7%)
Advantages	• More efficient • Requires less space • Long track record	• Less manufacturing costs • Very versatile • More shade tolerant • Less temperature sensitive
Disadvantages	• Costly • Limited applications • Shade intolerant • Temperature sensitive	• Shorter track record • Lower module efficiency • Requires more space
Applications	• Grid-connected PV systems • Standalone PV systems (off-grid)	• More used in standalone PV systems, such as portable solar chargers • Grid-connected PV systems
Market share	• 78 - 80%	• 18 - 20%

Table 3-1: Summary of Solar PV Cell Technologies [58].

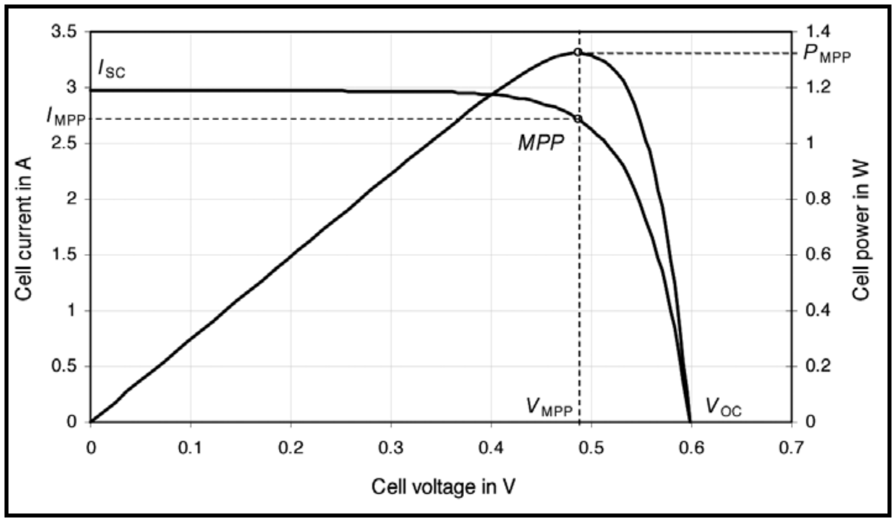


Figure 3-9: PV Cell Characteristic Curve [59].

The measurements taken for obtaining an I-V curve depend on controlling the load current. At open circuit, when no load current is generated, a first characteristic value can be measured; Voc. Decreasing the load fed by the photovoltaic module leads to a decreasing voltage with an increasing current I. Thus, increasing the load current from zero to its maximum value, the operating point moves from the open circuit voltage at zero current to the short circuit current Isc at zero voltage. The series of corresponding values of I and V, yield the characteristic I-V curve of the module [60].

3.3.4 Impact of Environmental Parameters on a PV Cell

- **Temperature:**

The temperature is a main environmental parameter that influences the power output considerably. A decrease in temperature would increase the max power at constant solar radiation; this is shown in figure 3-10 [54]. As for the I-V curve, shown in figure 3-11, the Voc is inversely proportionally influenced to the variation of the temperature. For crystalline silicon cells, every degree Celsius increase in temperature, Voc drops about 0.37%, while Isc increase approximately 0.05% [56].

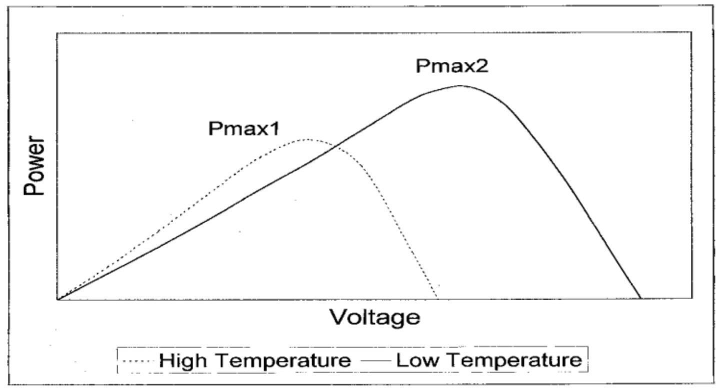


Figure 3-10: Impact of the Temperature on a PV Cell P-V Curve.

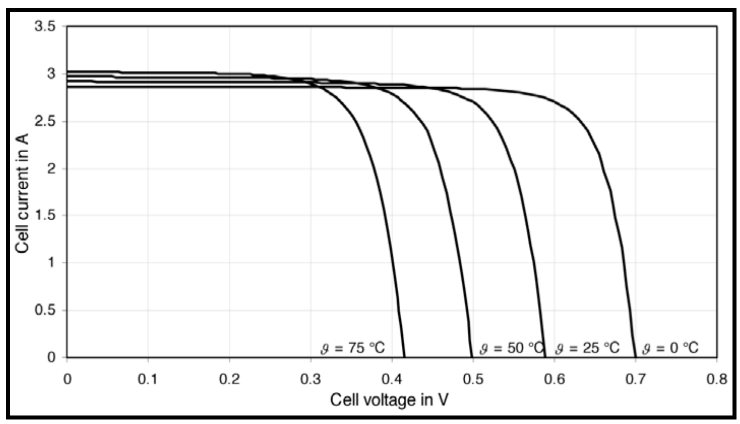


Figure 3-11: Impact of the Temperature on a PV Cell I-V Curve.

- **<u>Solar Radiation:</u>**

Solar Radiation (G) is a main factor affecting the power output of a PV cell. Figure 3-12 shows the impact of decreasing G at constant temperature of 25°C. The I_{sc} falls proportionally to the reduction in G, whereas the V_{oc} decreases slightly but not following a logarithmic relationship [56].

From the characteristic curves of the module, it is clear that the open circuit voltage of the photovoltaic module, the point of intersection of the curve with the horizontal axis, varies little with solar radiation changes. It is inversely proportional to temperature, i.e., a rise in temperature produces a decrease in voltage. On the other hand, the short circuit current, the point of intersection of the curve with the vertical axis, is directly proportional to solar radiation and is relatively steady with temperature variations. Actually, the photovoltaic module acts like a constant current source for most parts of its I-V curve.

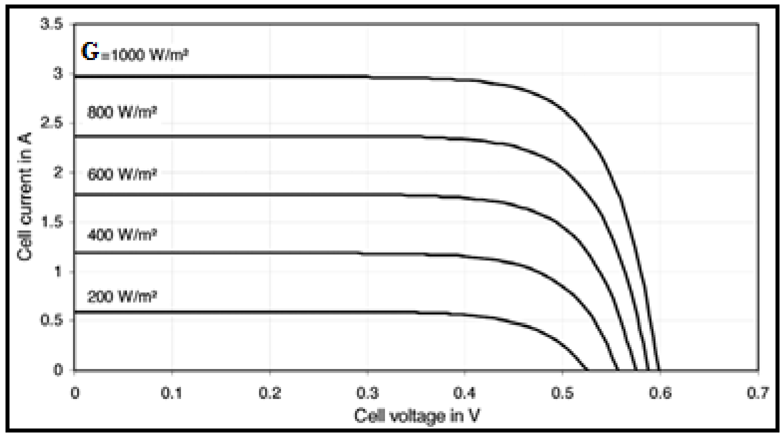


Figure 3-12: Impact of the Solar Radiation on a PV Cell I-V curve [59].

3.3.5 Impact of Other Parameters on a PV Cell

Figure 3-13 shows the extended equivalent circuit of a solar cell (one-diode model). Two resistances are modelled in the circuit to express different types of losses.

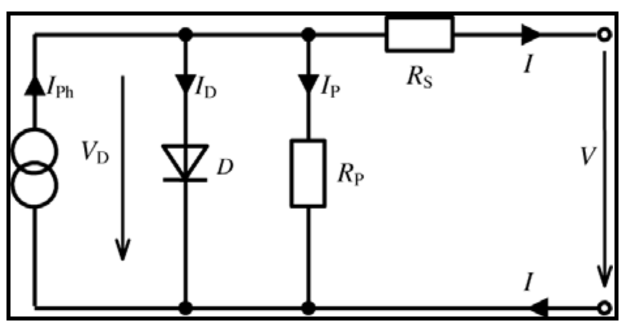


Figure 3-13: Extended Equivalent Circuit of a Solar Cell (One-diode Model)

- **<u>Series Resistance (R_s):</u>**

The series resistance accounts for the voltage drop due to the bond between the cell and its wire leads, and the resistance of the semiconductor itself (ideally, the value of this resistance should be zero) [56, 59]. Figure 3-14 shows the impact of increasing the R_s, which leads to a decrease in the P_{MPP}. R_s could be decreased by using wires of high efficiency.

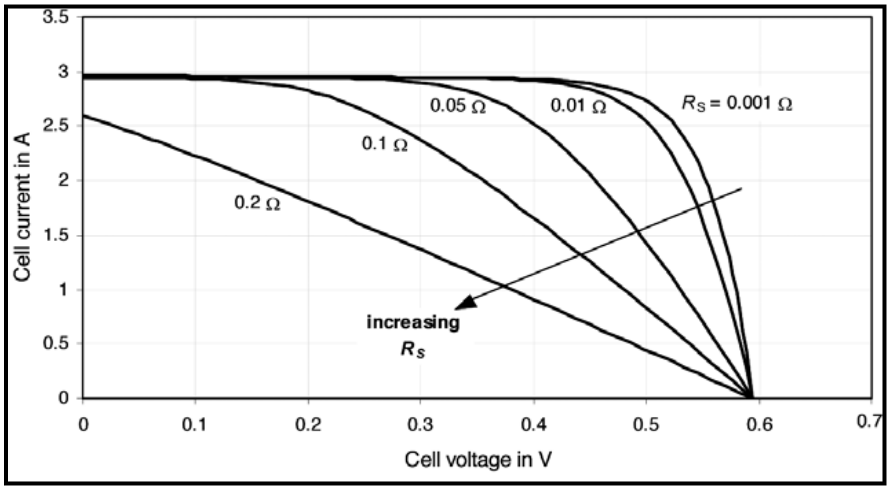


Figure 3-14: Impact of the Series Resistance Rs on the I-V Characteristics of a Solar Cell.

- **<u>Parallel Resistance (R_P):</u>**

The parallel resistance expresses the leakage current due to the impurities of the p-n junction. It should always be kept as value above 10Ω. As shown in figure 3-15, the impact of R_p higher than 10Ω is very small. However, a decrease in R_p would reduce the P_{MPP} [59].

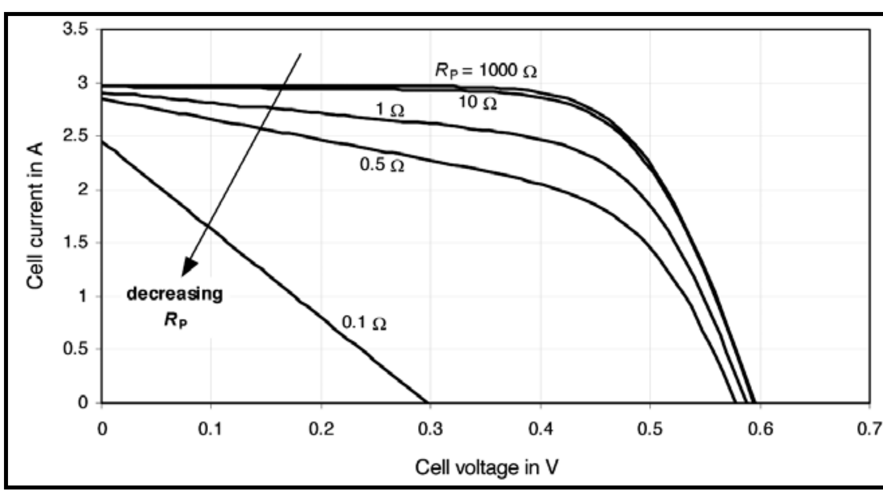


Figure 3-15: Influence of the Parallel Resistance R_P on the I-V Characteristics of a Solar Cell.

3.3.6 Connection of PV Cells

Solar cells are normally not operated individually due to their low output voltage. In photovoltaic modules, cells are mostly connected in series. A connection of these modules in series, parallel or series–parallel combinations builds up the photovoltaic system. Modules for grid connection would have many cells connected in series in order to obtain higher voltages [59,60].

- **Series Connection:**

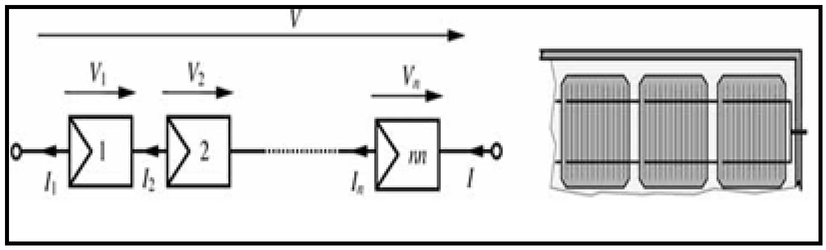


Figure 3-16(a): Series Connection of Photovoltaic Solar Cells

The current through all cells of a series connection of (m) cells is identical, according to Kirchhoff's law as shown in Figure 3-16(a). The cell voltages (V_i) are added to obtain the overall module voltage *V*. Connecting *m* modules in series will yield a PV string with a higher open-circuit voltage ($m \times V_{oc}$). Figure 3-16(b) show the I-V characteristic for any series connection.

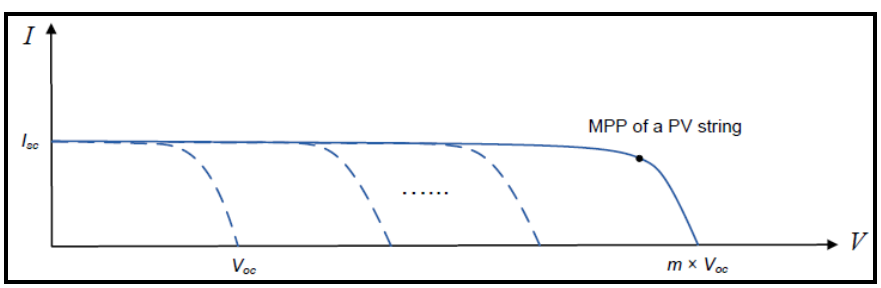


Figure 3-16 (b): I-V curve of a PV string with *m* modules in series.

- **Parallel Connection:**

Parallel connections are less often used than series connections because the associated current increase results in higher transmission losses. As shown in figure 3-17 (a) ,the voltage on all cells is constant and equal to that of the module's voltage (V), whereas the current accumulates from the (n) cells producing a total current (I) for the module. Figure 3-17(b) illustrates the I-V curve for the connection of (n) strings (of series cells) in parallel. This would create a PV array with a larger short-circuit current ($n \times I_{sc}$). Usually, large PV generators use modules with parallel cell strings of multiple series-connected solar cells as illustrated in figure 3-18.

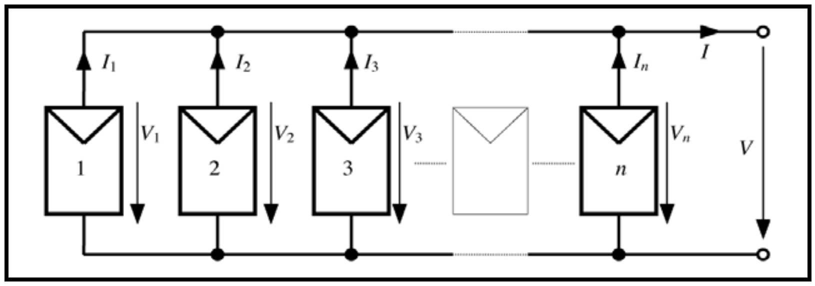


Figure 3-17(a): Parallel Connection of n Solar Cells

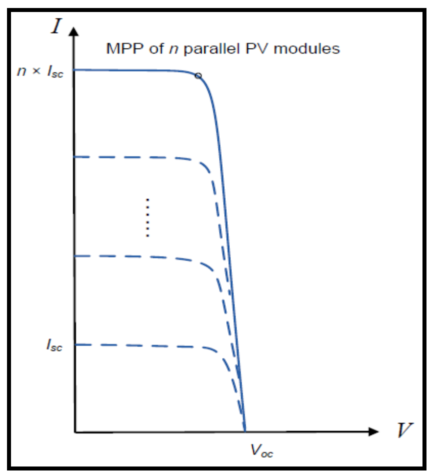


Figure 3-17(b): I-V curve of a PV String with *n* Modules in Parallel.

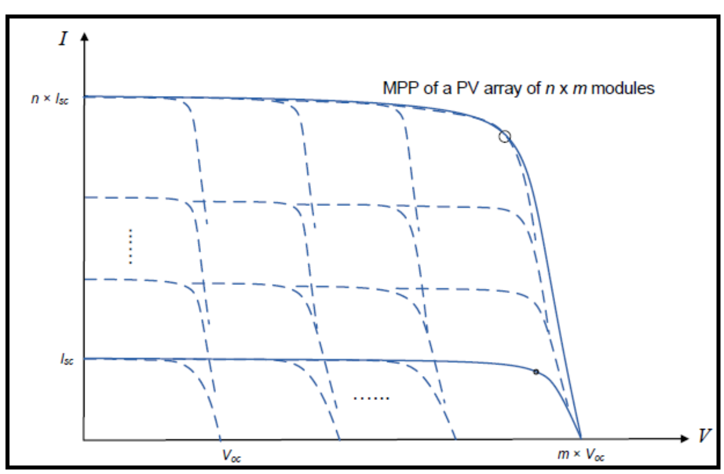


Figure 3-18: I-V curve of a PV array with combined series and paralleling modules.

3.4 Modeling of Grid-Connected PV System

Modeling of a grid-connected PV system is divided into two parts. First, the equivalent circuit for a PV model in figure 3-19 is used to obtain equations for the photovoltaic current and voltage which is solved using Newton-Raphson Method. Secondly, the DC power output of the PV Module is calculated then converted into AC power using an overall DC to AC derate factor.

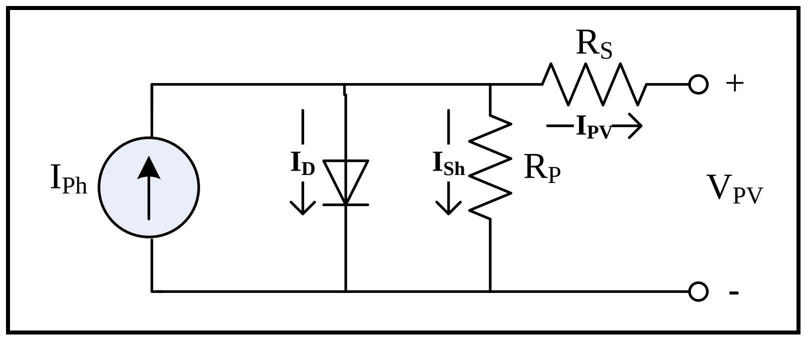


Figure 3-19: Equivalent Circuit for a PV model.

3.4.1 Mathematical Equations of Modelling Grid-Connected PV System

According to figure 3-19, the current output of a PV module (I_{PV}) is calculated using the light generated photo-current (I_{Ph}), the diode current (I_D) passing through the diode (accounting for the physical properties of the semiconductor cells) and the leakage current (I_{Sh}) passing through the cell parallel resistance (R_p) [11].

$$I_{PV} = I_{Ph} - I_D - I_{Sh} \tag{3-1}$$

$$I_{Ph} = I_{SC} G\left(1 + K_i (T_C - T_R)\right) \tag{3-2}$$

$$T_C = T_a + 0.2G \tag{3-3}$$

Where the ambient temperature (T_a) in Kelvin and solar radiation (G) in kW/m^2, are input values according to the location of implementation for the PV module. (T_R) is the reference temperature in Kelvin.

Using Shockley's Diode Equation, The diode current (I_D) in ampere [11]:

$$I_D = I_S\left(exp\left[q\frac{\left(V_{PV}/_n + I_{PV}R_S\right)}{AKT_C}\right] - 1\right) \qquad (3\text{-}4)$$

$$I_S = I_{OR}\left(\frac{T_C}{T_R}\right)^{3/_A} exp\left[\frac{qE_g}{KA}\left(\frac{1}{T_C} - \frac{1}{T_R}\right)\right] \qquad (3\text{-}5)$$

$$I_{OR} = \frac{I_{SC}}{exp\left[\frac{V_{OC}/_n}{V_t}\right] - 1} \qquad (3\text{-}6)$$

$$V_t = \frac{AKT_R}{q} \qquad (3\text{-}7)$$

Where, K is Boltzmann's constant (1.380658*10^{-23} J/K), q is the electron charge (1.6*10^{-19} C), E_g is the band gap energy for semiconductor (1.12eV for the silicon), I_{OR} is the reverse saturation current of diode in ampere, V_t is the thermal voltage in volt and V_{pv} is output voltage from the PV module. Thus,

$$I_{PV} = I_{Ph} - I_S\left(exp\left[q\frac{\left(V_{PV}/_n + I_{pv}R_S\right)}{AKT_C}\right] - 1\right) - \frac{V_{PV}/_n + I_{pv}R_S}{R_P} \qquad (3\text{-}8)$$

Ideality Factor (A) according to [7]:

$$A = \frac{V_{mpp}\left(I_{sc} - I_{mpp}\right)}{q}10^{-20} \qquad (3\text{-}9)$$

Cell series resistance (R_S) according to [7]:

$$R_S = \frac{V_{mpp} - \ln\left(\frac{I_{SC} - I_{mpp}}{I_{SC}}\right)\left(I_{mpp} - I_{SC}\right)\left(\frac{V_{mpp}}{I_{mpp}}\right) + V_{OC}}{I_{mpp}}10^{-3} \qquad (3\text{-}10)$$

$$P_{PV} = I_{PV} \cdot V_{PV} \tag{3-11}$$

The P_{PVA} (photovoltaic array power) can be calculated using the number of PV modules connected in series (N_S) and parallel (N_P) by [61]:

$$P_{PVA}\ (DC) = N_P I_{PV} \cdot N_S V_{PV} \tag{3-12}$$

The grid interconnection of a PV system is accomplished through the inverter, which converts DC generated power from the PV modules to AC power that could be fed into the grid. This could be modelled through an overall DC to AC derate factor calculated as a product of all the derate factors for the components of the PV system [56, 62]. For this PV system of the research, the assigned derate factor is 0.77 according to [63,64].

$$P_{PVA}\ (AC) = 0.77 \cdot N_P I_{PV} \cdot N_S V_{PV} \tag{3-13}$$

3.4.2 Newton-Raphson Algorithm

Newton-Raphson is the most commonly used method for solving simultaneous non-linear equations numerically. It is a successive approximation procedure based on an initial estimate of the unknown (V_{pv}) [65].

Equation (3-8) is re-arranged to equation (3-14), and equated to zero:

$$f(I_{pv}) = I_{Ph} - I_S\left(exp\left[q\frac{(V_{PV}/_n + I_{PV}R_S)}{AKT_C}\right] - 1\right) - \frac{V_{PV}/_n}{R_p} - I_{PV}\left(1 + \frac{R_S}{R_p}\right) \tag{3-14}$$

$$I_{PV(i+1)} = I_{PV} - \frac{f(I_{PV})}{f'(I_{PV})} \tag{3-15}$$

$$E_r = abs\left(\frac{I_{PV(i+1)} - I_{PV(i)}}{I_{PV(i+1)}}\right) * 100 \tag{3-16}$$

The principle of Newton-Raphson approximation algorithm is based on an initial guess of the root of f(Ipv)=0 at I_i, then a better guess is obtained at I_i+1 as defined in (3-15). Successive iterations are obtained until the calculated relative approximate error (Er) becomes equal to the pre-defined error tolerance (Ea). Matlab® software is used to model the equations (3-1) to (3-16).

The PV model obtained is based only on datasheet values. The PV model was implemented on Matlab® software using different datasheets for different types of PV cells. PV Module characteristic curves were simulated and compared to reference ones available on PV Module's datasheet (appendix A, B and C) to verify the model. Results are simulated and discussed in chapter 5.

The PV model was extended for reliability studies by varying two inputs; solar radiation and temperature. The PV model is capable of accommodating any location in the world. The inputs needed for the PV model for reliability studies were hourly temperature and solar radiation for a year. The hourly temperature values were collected for a year, and the solar radiation values were obtained using mathematical equations.

3.4.3 Solar Radiation Calculation

Picking a suitable location is an essential step of a photovoltaic system design. Even a well-established solar system with good component parameters and configuration cannot have desired power output if it is not installed at an appropriate place of high solar radiation.

Figure 3-20 shows the solar radiation (G) by regions of the world, where higher energy potential is in the white area [54]. The solar radiation is calculated for any location in the world based on the geographical location, day of the year and time of the day.

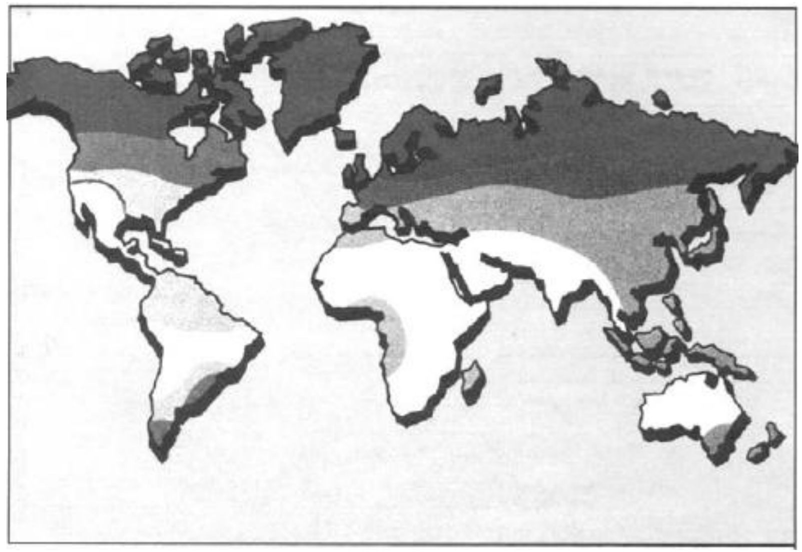


Figure 3-20: Solar Radiation by Regions of the world.

The solar radiation (G) in kW/m^2 can be calculated at the instant of any hour during the year based on the geographic location, day and the time [66-68].

$$G = \frac{G_n}{1000}(\sin\emptyset \sin\delta + \cos\emptyset \cos\delta \cos\omega) \tag{3-17}$$

Where,

G_n is the beam radiation measured in the direction of the rays on the (n day) of the year in W/m^2 and n is the day number of the year (varies between 1 and 365).

(Φ) is the latitude of the location in degrees, and is defined as the angular location north or south to the equator ($-90° \leq \Phi \leq 90°$, $\Phi > 0$ for north).

(δ) is the declination of the sun in degrees, and is defined as the angular position of the sun at solar noon with respect to the plane of the equator ($-23.45° \leq \delta \leq 23.45°$, $\delta>0$ for north).

(ω) is the solar hour angle in degrees, and is defined as the angular displacement of the sun east or west of the local meridian due to the rotation of the earth on its axis at 15°/hour, negative before solar noon and positive after solar noon.

All of which can be calculated by:

$$G_n = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \tag{3-18}$$

$$\delta = 23.45\sin\left(\frac{360}{365}(284+n)\right) \tag{3-19}$$

$$\omega = 15(12 - AST) \tag{3-20}$$

$$AST = LST + \frac{ET - 4(SM - LL)}{60} \tag{3-21}$$

$$ET = 9.87sin(2B) - 7.53cos(B) - 1.5sin(B) \tag{3-22}$$

$$B = \frac{380}{364}(n - 81) \tag{3-23}$$

G_{sc} is the solar constant (1366 W/m^2). Where as, AST is the apparent power time and LST is the local standard time, both are in minutes from midnight. ET is the equation of time, SM is the standard meridian for local time zone in degrees and LL is the local latitude in degrees east and west Greenwich meridian.

The solar equations discussed were used to calculate the hourly solar radiation for two locations in Egypt; Hurghada and Cairo (longitude and latitude values were taken from Appendix D). The two locations were picked based on [40], where a study was carried out to estimate the solar radiation in six different cities in Egypt. It was observed that Hurghada has the greatest solar radiation among the six cities, whereas Cairo has the least. However, Cairo accommodates a large portion of the electrical demand due to its high population. A comparison for the PV power obtained from the photovoltaic system located in the two locations was simulated using Matlab® software package. Simulations and discussions are in chapter 5.

Figure 3-21 illustrates the flow chart of the algorithm used to model a grid-connected PV system. The model requires three inputs; datasheet parameters' values according to the PV module datasheet, calculated solar radiation and collected temperature according to the location picked. The inputs are substituted in the PV model equations forming a non-linear relation, which is solved using Newton-Raphson Method. The total DC PV array power is calculated using the PV’s current and voltage obtain from the non-linear solution. The DC power is converted into AC power using an assigned DC to AC derate factor.

The model is extended to be used for reliability studies by calculating the hourly AC power produced from the PV system. This requires an hourly temperature and solar radiation input values, as they are the influential parameters in the PV output power obtained. The hourly PV power is added to the Egyptian Unified Grid modeled in chapter 4. Simulation and results are discussed in chapter 5.

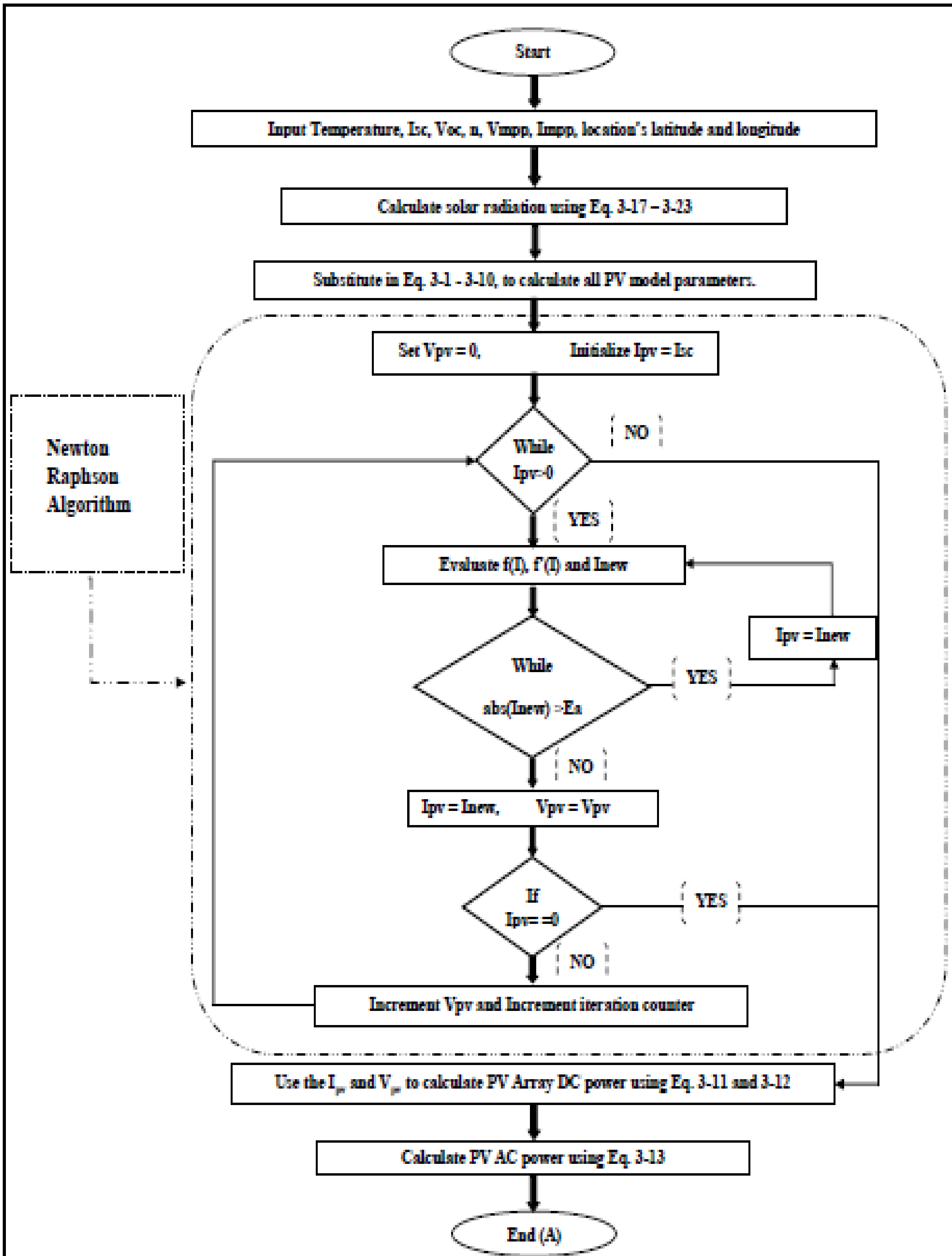


Figure 3-21: Flow Chart of Grid-Connected PV Model.

Chapter Four

4 RELIABILITY ANALYSIS FOR THE UNIFIED NETWORK CONTAINING PV PLANT

4.1 Introduction

During the recent years, an attention towards the utilization of solar energy in order to satisfy the electrical demands has been widely increasing around the world. Solar power generation plants have been integrated into existing power systems, which led to the necessity of evaluating the reliability of these plants and assess the impacts they would have on the overall system reliability.

This chapter focuses on the reliability aspects of the power generation of a large unified network, pick to be the Unified Network of Egypt (UNE). The electrical network is modelled through its load data and the generation conventional units available. The PV model described in the previous chapter is added to the modelled network to study its impact. Reliability indices were calculated in several cases with and without the integration of PV system to form an accurate impression on PV system's impact on the UNE.

4.2 Power System Reliability Concepts

Reliability is a measure of the ability of a system to perform its designated functions under the conditions it was designed to operate. In the context of power system, reliability is a measure of the ability to deliver electricity to all points of utilization under both static and dynamic conditions, with a mutually acceptable assurance of continuity, quality and in the amount desired. Power systems reliability assessment, both deterministic and probabilistic, is divided into two basic aspects; system adequacy and system security as shown in figure 4-1 [69].

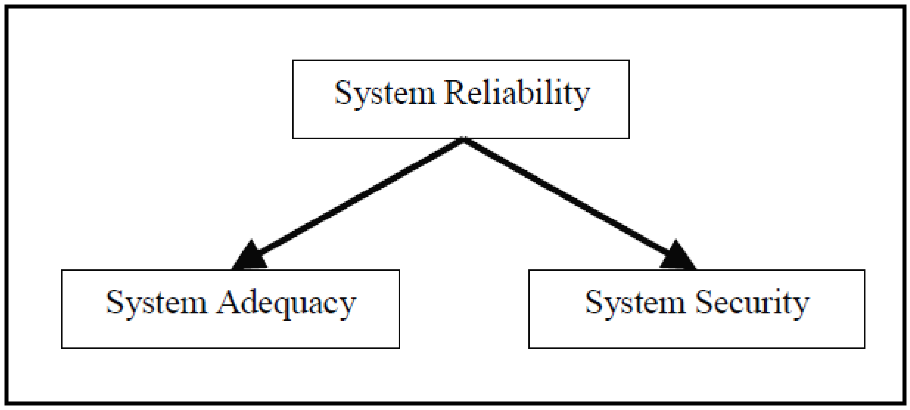


Figure 4-1: Subdivision of System Reliability.

- **System Adequacy:**

It is related to the existence of sufficient facilities within the system to satisfy the customer demand. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual customer load points. It is therefore associated with static conditions, which does not include system disturbances [69].

- **System Security:**

It is related to the ability of the system to respond to disturbances arising in the system, such as dynamic, transient, or voltage instability situations. Under such condition, security studies show system ability to survive without cascading failures or loss of stability [69].

Most of the probabilistic techniques presently available for reliability evaluation are in the domain of adequacy assessment. This is due to the complexities associated with modelling the system in the security domain. Adequacy assessment methods in power systems are applied to three different hierarchical levels as shown in Figure 4-2 [69, 70]. At hierarchical level I (HLI), the total system generation is examined to determine its adequacy to meet the total system load requirements. Reliability assessment at HL-I is only concerned with estimating the necessary generation capacity to satisfy the demand. It is normally defined as generating capacity reliability evaluation. At hierarchical level II (HL-II), reliability evaluation includes both the generation and transmission in an assessment of the integrated ability of the composite system to deliver energy to the bulk supply points. It can be used to assess the adequacy of an existing or proposed system including the impact of various reinforcement alternatives at both the generation and transmission levels. This analysis is usually termed as composite system or bulk power system reliability evaluation. An overall assessment considering all three functional segments is known as hierarchical level III (HLIII) analysis. This is considered the most complex level as it involves all three functional zones, starting at the generating stations and terminating at the individual customer load points. The research described in this thesis is conducted at HL-I.

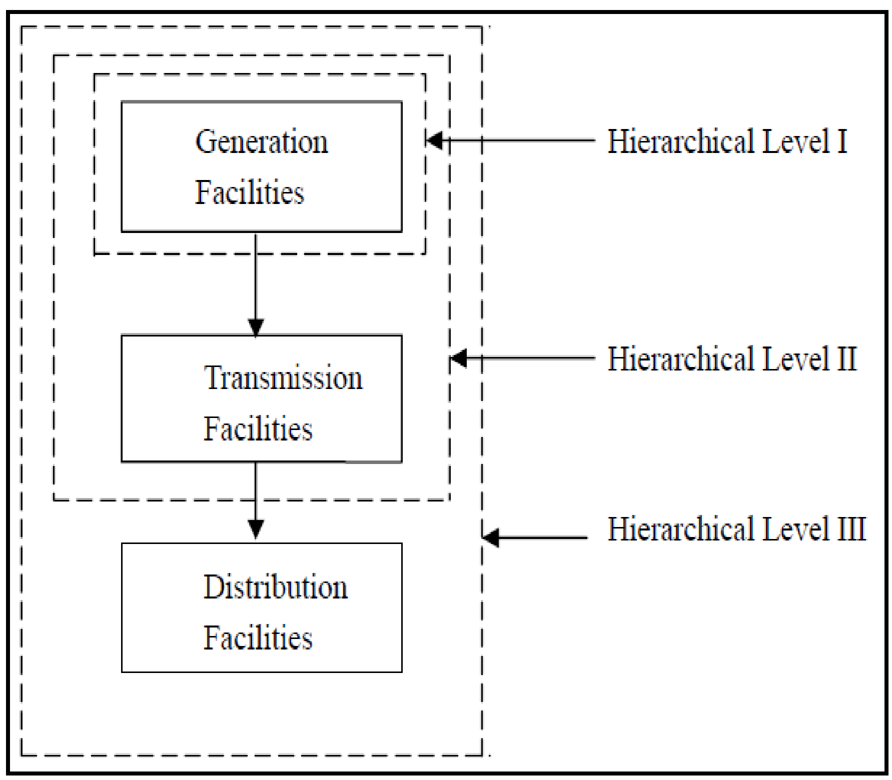


Figure 4-2: Hierarchical Level Structure.

4.3 Reliability Indices Used for HLI

This research considers only the adequacy indices for HLI (hierarchical level I) which is concerned with the generation facilities, where the total system generation is examined to determine its adequacy to meet the total system load requirement. The basic modelling approach in an HL-I analysis is shown in Figure 4-3. The generation model and the load model are combined to produce the risk model. The risk indices obtained are overall system adequacy indices and do not include transmission constraints and transmission reliabilities. There are three main indices used to measure the performance of HLI [69, 70]:

- **LOLE:**

LOLE (loss of load expectation) in hr/yr. It indicates the average number of hours for which the hourly load is expected to exceed the available generating capacity during a year. This is calculated using equation (4-1).

$$\mathrm{LOLE} = \sum_{j=1}^{N} t_j \tag{4-1}$$

- **LOEE:**

LOEE (loss of energy expectation) in MWh/yr. It indicates the amount of energy that was unsupplied due to the load demand exceeding the available generating capacity during a year. This is calculated using equation (4-2).

$$\mathrm{LOEE} = \sum_{j=1}^{N} E_j \tag{4-2}$$

- **LOLF:**
  LOLF (loss of load frequency) in occurrence/yr. It indicates the number of times the load demand exceeded the generating capacity during a year. This is calculated using equation (4-3).

$$LOLF = \sum_{j=1}^{N} F_j \tag{4-3}$$

Where,

j is the number of load failure.

N is the total number of failures per year.

t_j is the duration of the j-th failure.

E_j is the unsupplied energy at the j-th failure.

F_j is the number of failures.

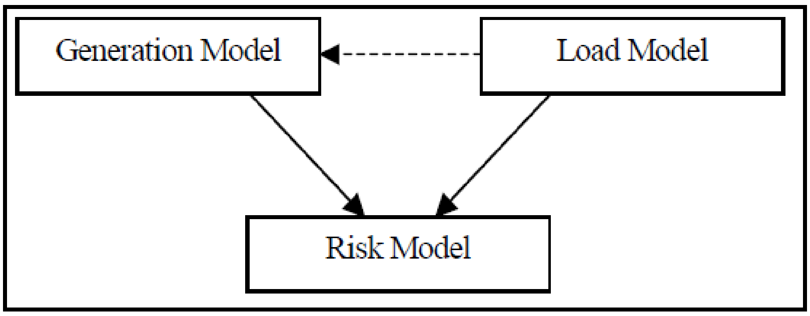


Figure 4-3: Conceptual Tasks for HLI Evaluation.

4.4 Reliability Evaluation Techniques

Reliability analysis of a power system can be conducted using either deterministic or probabilistic techniques. Earlier, the criteria and techniques used in practical applications were all deterministically based. These techniques involved percentage reserve methods, where the required reserve is a fixed percentage of either the installed capacity or the predicted load. Other criteria were also used, such as a reserve equal to one or more of the largest units. The essential weakness of deterministic criteria is that they do not respond to the probabilistic nature of system behaviour, customer demands or component failures. System behaviour is probabilistic in nature, and therefore it is logical to consider probabilistic methods that are able to respond to the actual factors that influence the reliability of the system [69]. Limited computational resources, lack of data and evaluation techniques have limited the use of probability methods in the past. This is no longer valid today, as a number of publications associated with the development and application of probabilistic techniques in power system reliability evaluation is available [71-74]. The research described in this thesis extends the probabilistic evaluation of power systems incorporating renewable energy.

There are two main categories of evaluation techniques applied in power system reliability evaluation; analytical methods and simulation methods. Analytical methods represent the system by mathematical models and evaluate the reliability indices using direct numerical solutions. Simulation methods estimate the reliability indices by simulating the actual process and random behaviour of the system. Both methods have their merits and demerits. In general, analytical techniques are best used for a system of non-complex operating conditions with low component failure probabilities. Whereas, for systems having complex operating conditions involving a relatively large number of severe events and considerations need to be incorporated, Monte Carlo Simulation (MCS) are often preferable. The availability in recent years of high speed computing capability has made MCS a viable technique for many areas of power system reliability evaluation and it can be used to provide information not generally available from the basic analytical approaches. In [75, 76] the authors studied the two methods for reliability estimation, and it was found that MCS method was the only feasible approach to the estimation of reliability particularly of large complex systems.

4.4.1 Monte Carlo Simulation Technique

Monte Carlo methods are more flexible when complex operating conditions and system considerations need to be incorporated. A MCS procedure treats the problem as a series of “real” experiments, whose outcomes depend on the operating characteristics of the components and of the system. The reliability indices are then estimated by observing the experiments. Considerable work has been done on the application of Monte Carlo simulation [75, 77-79]. Monte Carlo has been used for power system reliability evaluation simulation; by using utilized random number generators and probabilistic techniques to model the behaviour of the power system. Figure 4-4 illustrates the flow chart of MCS Method [78]. MCS applications in power system reliability assessment can be categorized as being "sequential" or "non-sequential" procedures. A sequential approach moves through time sequentially or chronologically and the system states are simulated indirectly. A non-sequential process considers each time point independent of another without considering transitions between system states. The sequential simulation method is used in this research as it can simulate chronological issues and provide additional time related indices such as frequency and duration of load loss. Sequential techniques are widely used for power system reliability evaluation. The sequential technique of state duration approach is used to conduct some of the reliability studies described in this thesis.

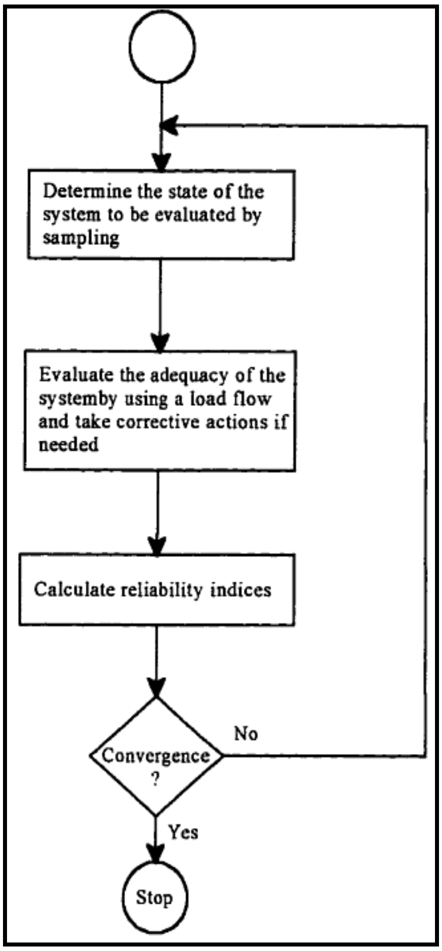


Figure 4-4: Logic Diagram of Monte Carlo Simulation Method.

4.4.2 Sequential Method: State Duration Approach

The sequential or state duration approach is based on sampling the probability distributions of the component state durations. This technique is applied through following steps [46, 69, 70]:

Step 1: Specify the initial state of each component. Generally, it is assumed that all components are in the up state.

Step 2: Sample the duration of each component residing in its present state. Each individual component in the system is represented by a two-state. In the two state models, the generating unit is considered to be either fully available (Up) or totally out of service (Down) as shown in Figure 4-5.

$$T_{ON} = -MTTF\ln(\lambda) \tag{4-4}$$

$$T_{OFF} = -MTTR\ln(\mu) \tag{4-5}$$

Where, (λ) is the unit failure rate and (μ) is the unit repair rate. Each of which is a uniformly distributed random number between [0, 1]. MTTF is the mean time to failure and MTTR is the mean time to repair. T_{ON} and T_{OFF} presents the periods of time when the component is available and unavailable respectively.

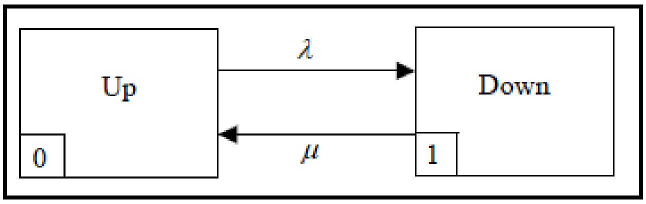


Figure 4-5: State Duration Approach.

Step 3: Repeat Step 2 in a given time span of one year (8760 hours). A chronological curve is then constructed in the given time span based on the up and down state during (T_{ON}) and (T_{OFF}) respectively.

Step 4: The simulated operation is assessed for each hour during the given time span of one year.

Step 5: At the end of each simulated year, the reliability indices are calculated and updated. Then, MCS technique is used for the convergence of these results after a long time of simulation.

4.5 Proposed Algorithm

A proposed algorithm is suggested to investigate the reliability impact of connecting a 140MW PV system implemented virtually in Hurghada to the Egyptian Unified Grid (EUG). This was carried out through 3 main steps; modelling the PV system, modelling the EUG and calculating required indices for reliability evaluation. Figure 4-5 illustrates the flow chart of the proposed algorithm.

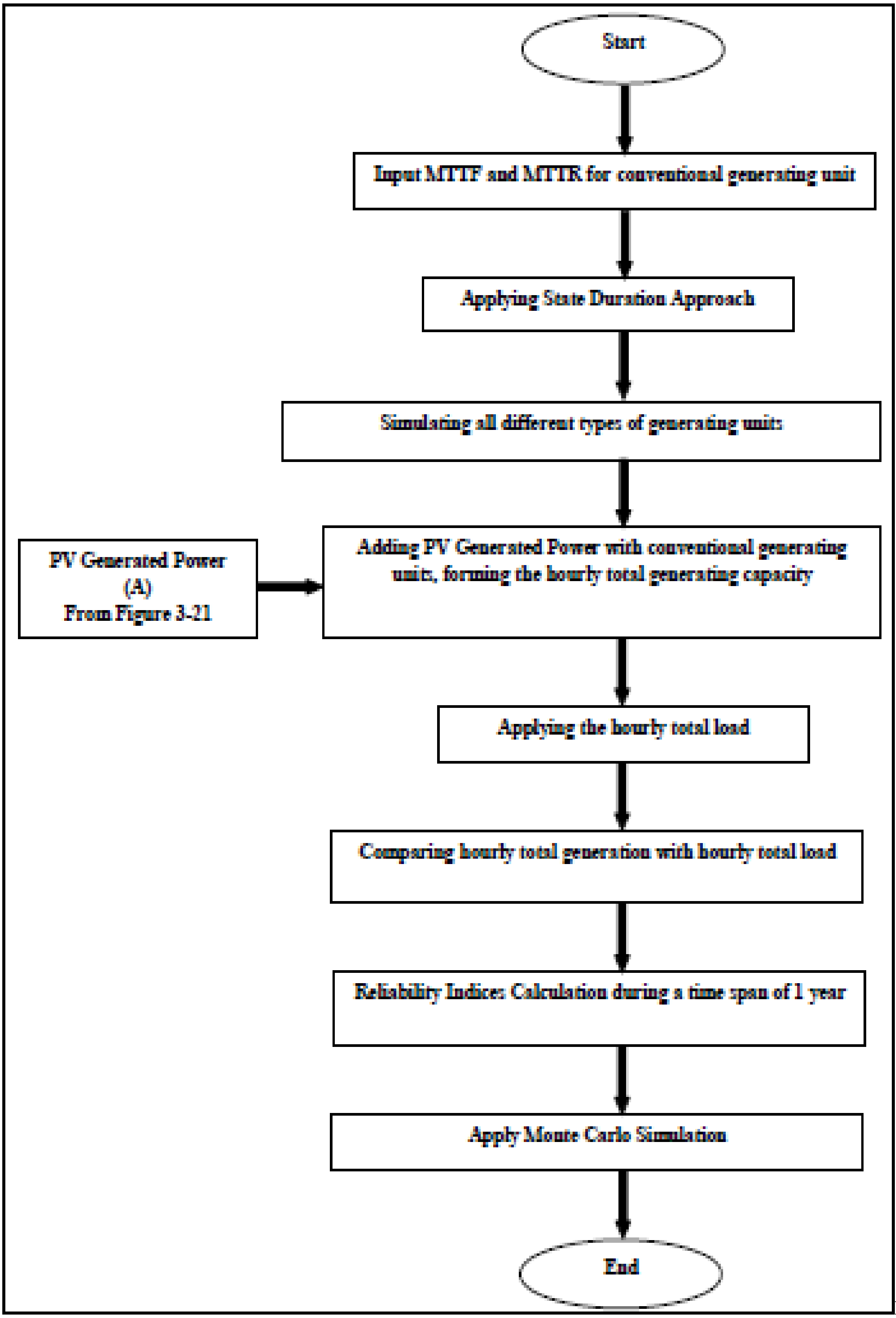


Figure 4-5: Flow Chart of the Proposed Algorithm.

4.5.1 Modelling PV system.

A 140MW PV system is modelled and simulated on Matlab® software package using Sharp NU-E245 (J5) datasheet parameters [Appendix A]. Input temperature values for Hurghada were collected, whereas for Hurghada's solar radiation, it was calculated using equations (3-17 – 3-23). The hourly output power is calculated using the proposed algorithm discussed in the previous chapter.

4.5.2 Modelling of Large Electrical Network: (The Egyptian Grid)

The Unified Electrical Network of Egypt is modelled to present a large electrical network. The model is based on conventional generating units that already exist in Egypt. Those conventional generating units supplying the total load demand available in the whole country. The total load demand is also modelled to be compared to the generated capacity, in order to analyse the reliability performance.

- **Modelling Conventional Generating Units**

The Unified Electrical Network of Egypt consists of four different types of conventional generating units; steam, gas, hydro and combined cycle. All of which are simulated using state duration sampling approach. Table 4-1, presents a summary for the conventional generating units. Figure 4-6 illustrates the Egyptian map with black circles presenting the conventional units. Each conventional unit is simulated as a two state model, as shown in Figure 4-7. The conventional unit's data; MTTF, MTTR, FOR and rated power is collected from the ministry of electricity's annual report [80].The data collected for each unit is used for the simulation of the generated unit output power. This simulation technique provides an accurate presentation for the given network, as it presents different generation types during each hour for each unit. The total generated power of the Unified Electrical Network of Egypt is simulated by summing up the hourly conventional generated power of each unit.

Type of Generation	Number of Units	Rated Power Range (MW)
Steam	60	26.5 - 341.25
Gas	31	12.5 - 250
Hydro	29	15 – 175
Combined Cycle	40	24.2 – 250

Table 4-1: Conventional Generators.

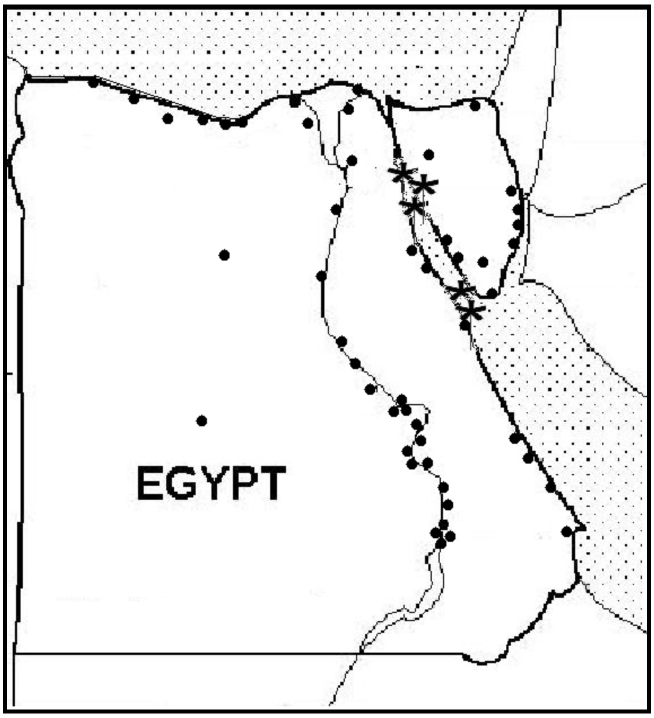


Figure 4-6: Map of Egypt [81].

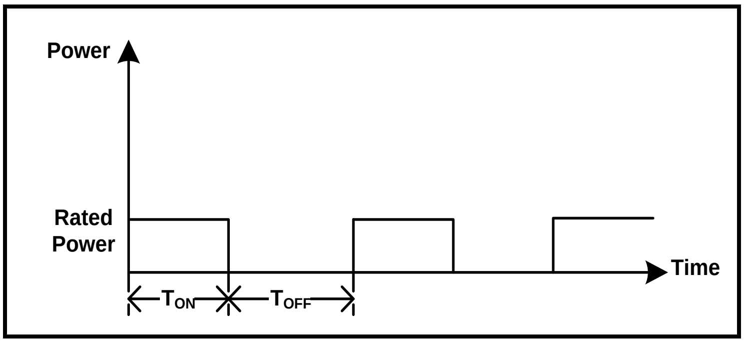


Figure 4-7: Two-State Generating Unit.

- **<u>Load Model</u>**

The load model is the main scope of the generation, as it is the demand which the generation tries to satisfy. It has an essential role in judging the reliability performance of the generating system. The load is hourly compared to the total generation to record any shortage. The load varies throughout the year and keeps escalating each year. In a sequential Monte Carlo procedure, the system load is represented by a chronological hourly load model. According to that, an hourly load model is simulated for a year based on actual recorded data from the Unified Electrical Network of Egypt.

4.5.3 Reliability Evaluation

The total generated power available can be simulated by combining the total hourly conventional generated power with the total hourly PV power. Reliability analysis is then conducted by incorporating the load models. The total generated power is compared with the load model in order to calculate the reliability indices; LOLE, LOEE and LOLF. MCS technique is used for the convergence of the results after a long time of simulation through the model. Different cases were simulated to emphasis the impact of PV power addition to the Unified Electrical Network of Egypt.

- **<u>Case 1: Addition of PV Power to the Total Conventional Power.</u>**

Reliability indices are calculated during two procedures. First, the total conventional power, without the addition of PV is compared to the load model. Then secondly, the total conventional power combined with the PV power is compared to the load model.

- **<u>Case 2: Increasing Load</u>**

The same procedures of the first case are carried out again, but with an increase in load. The load is increased by 5%, 10% and 15%. For each increment in load, the total generation with and without the integration of PV power is compared.

- **Case 3: Effect of variation in DC to AC derate factor.**

As mentioned previously in 3.2, the DC to AC conversion is done through an assigned derate factor. The derate factor is reduced and increased to study its effect on the reliability performance.

- **Case 4: Substitution of Conventional Power with Unconventional (PV) Power.**

As 140MW of unconventional (PV) power is injected into the grid, a corresponding 140MW power is excluded from the grid. This gives an indication of the performance of the unconventional power compared to the conventional power.

The simulation and results of all the cases are discussed in chapter 5.

C h a p t e r F i v e

5 SIMULATIONS & RESULTS

This chapter shows the results obtained by the Matlab® simulations. The PV model described in chapter 3 is verified using different types of module datasheets. The PV model was tested under variable temperatures and solar radiations, showing the differences in its characteristic curves. The PV model was accommodated in two different locations in Egypt; Cairo and Hurghada. A comparison was carried out to show the performance of each during the four seasons and against load. Further studies were carried out to show the reliability performance of the PV model implemented in Hurghada in different cases; during an increase in load, for changes in DC to AC derate factor and for an equivalent capacity decrease in the conventional generation.

5.1 Verification of PV model

The PV model implemented previously in chapter 3, was tested using different types of PV module datasheets. Figures 5-1, 5-2 and 5-3 show the I-V and P-V curves for a mono-crystalline PV module [Appendix A], poly-crystalline PV module [Appendix B] and thin film PV module [Appendix C] respectively. The I-V and P-V curves were compared to those previously discussed in figure 3-9 along with those available in the datasheet of each type, to ensure the correct performance of the PV model. It was found that the simulated PV is very accurate and does not exceed 5% error.

5.1.1 Mono-Crystalline PV module

Parameters of Module NU-E245(J5) [Appendix A] were used to verify the PV model implemented for a Mono-Crystalline PV type. Figures 5-1(a) and (b) show the characteristic curves for this PV type.

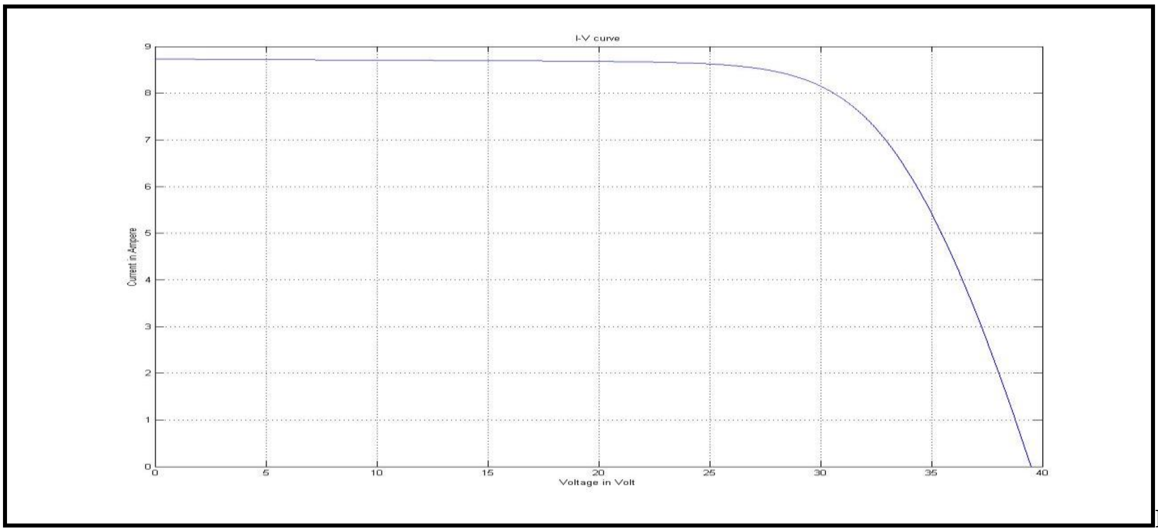


Figure 5-1 (a): I-V Curve for a Mono-Crystalline PV Module.

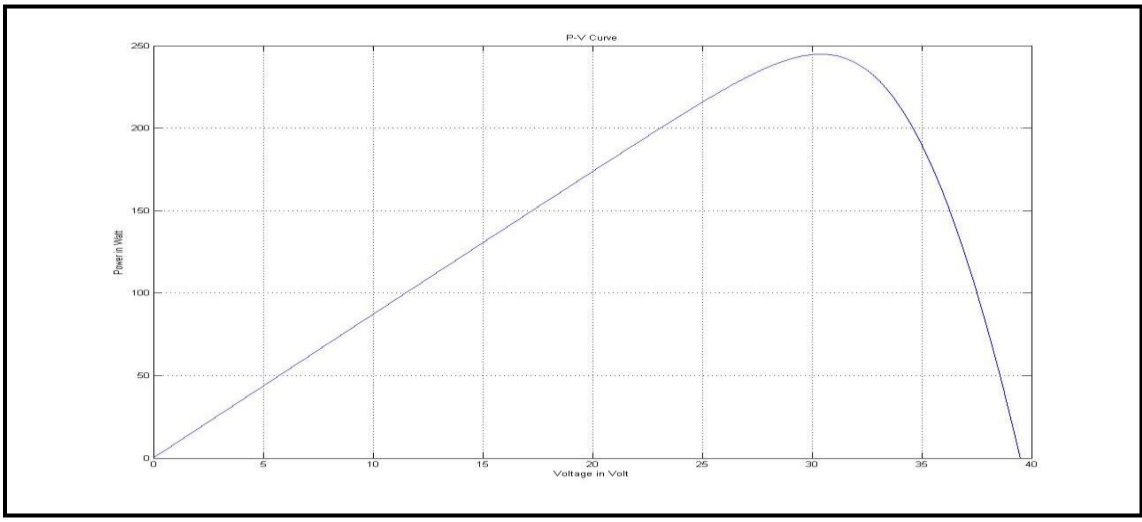


Figure 5-1 (b): P-V Curve for a Mono-Crystalline PV Module.

5.1.2 Poly-Crystalline PV module

Parameters of Module TSM-PC05-235 [Appendix B] were used to verify the PV model implemented for a Poly-Crystalline PV type. Figures 5-2(a) and (b) show the characteristic curves for this PV type.

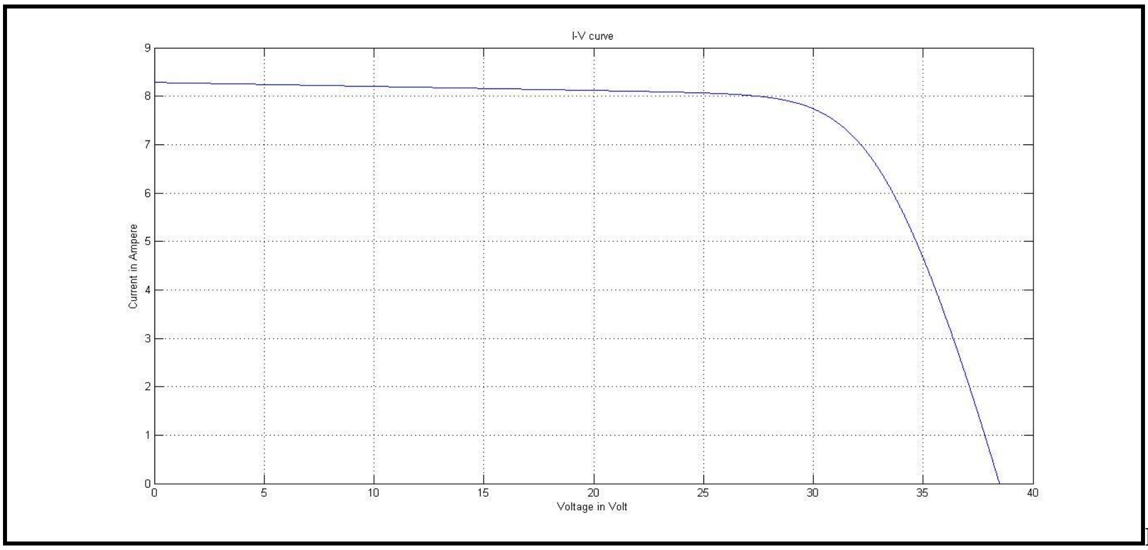


Figure 5-2 (a): I-V Curve for a Poly-Crystalline PV Module.

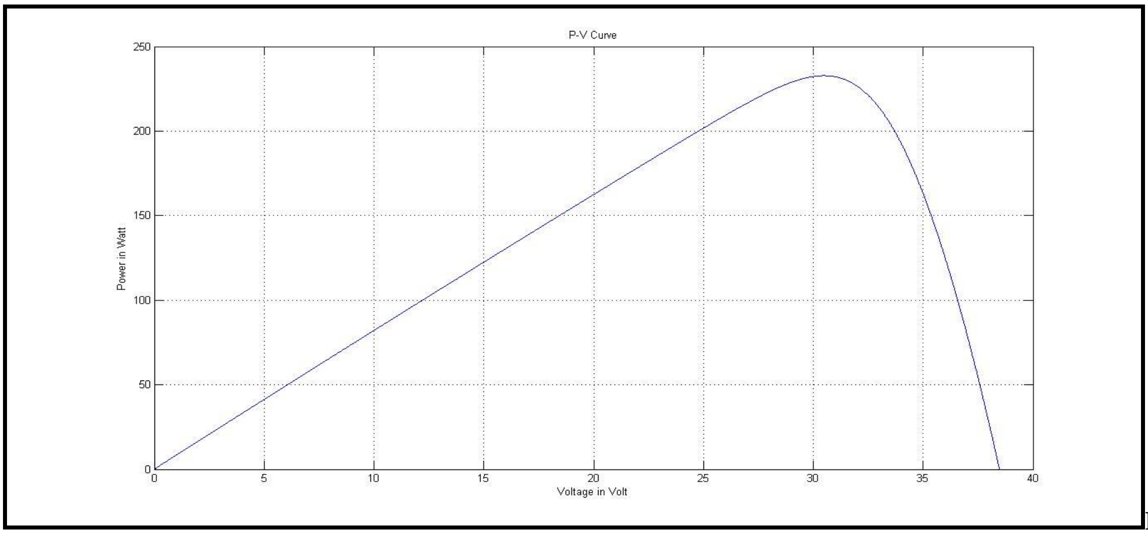


Figure 5-2 (b): P-V Curve for a Poly-Crystalline PV Module.

5.1.3 Thin Film PV module

Parameters of Module FS-87.5 [appendix C] were used to verify the PV model implemented for a Thin Film PV type. Figures 5-3(a) and (b) show the characteristic curves for this PV type.

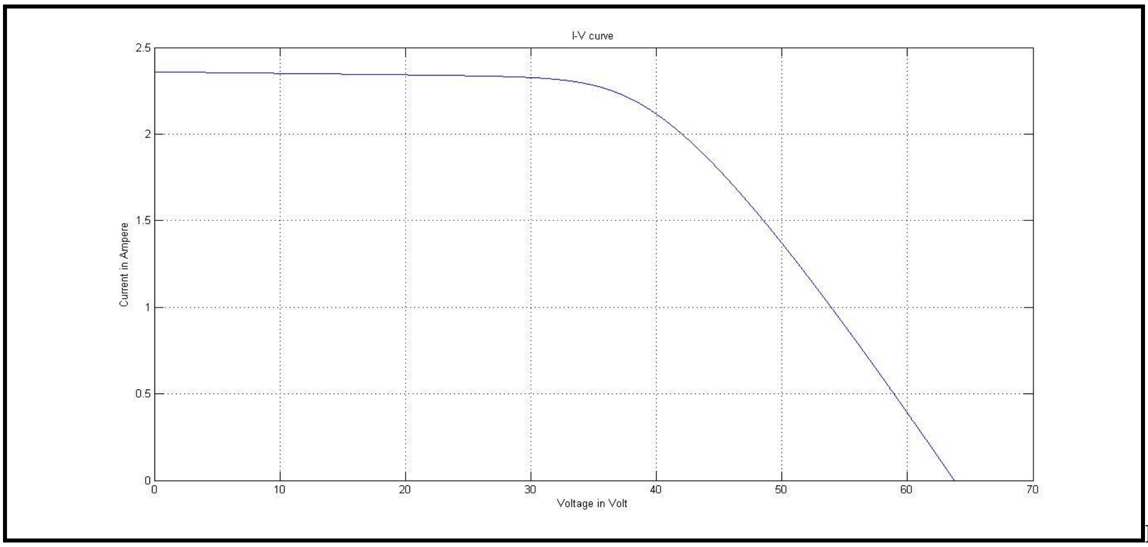


Figure 5-3 (a): I-V Curve for a Thin Film PV Module.

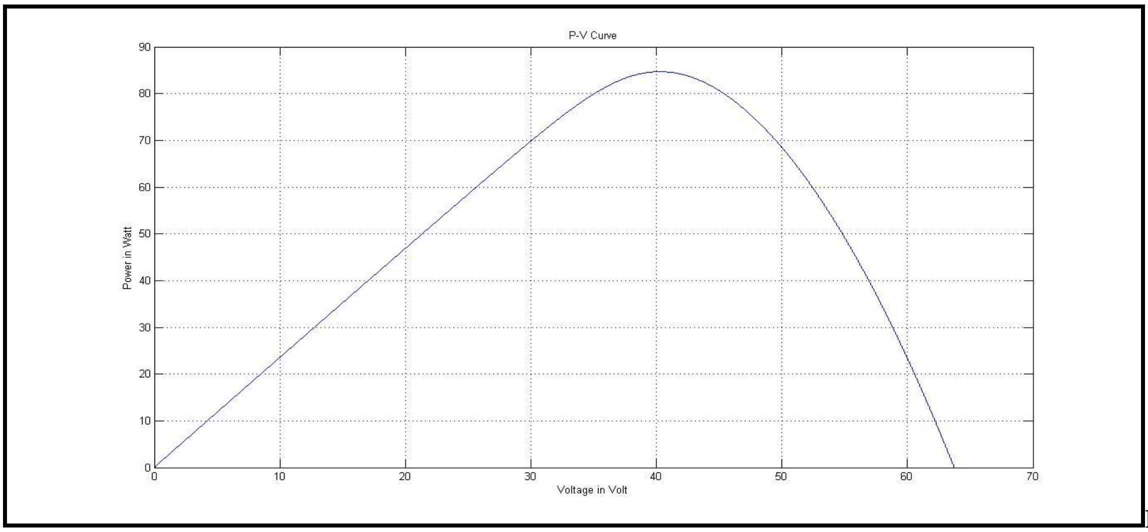


Figure 5-3 (b): P-V Curve for a Thin Film PV Module.

5.2 Variation of environmental parameters

Temperature and solar radiation are two important environmental parameters that affect the characteristic curves and performance of a PV module. Figures 5-4 show the I-V and P-V curves for the variation of temperature. Whereas, figures 5-5 show the I-V and P-V curves for the variation of solar radiation. The curves were compared to those previously discussed in figures 3-10 - 3-12 and those available on the module's datasheet, to verify the implemented PV model.

5.2.1 Variation of Temperature

Figures 5-4 shows the impact of temperature variation on the PV cell's characteristic curve at constant solar radiation. It can be observed that an increase in temperature would lead to a decrease in the power output. An increase in cell temperature causes the voltage to move leftward, while decreasing temperature produces the opposite effect.

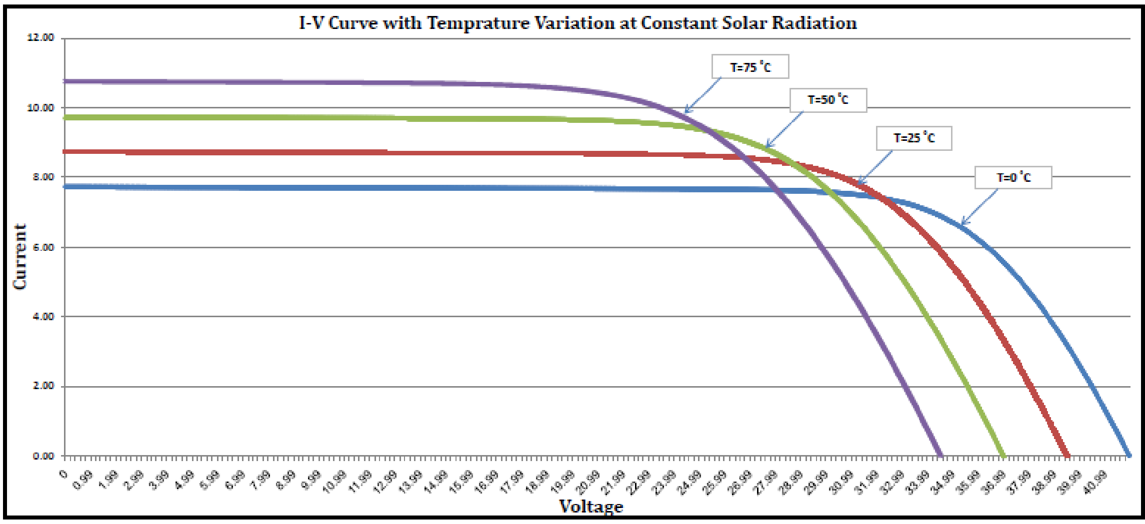


Figure 5-4 (a): I-V Curve for Temperature Variation at Constant Solar Radiation

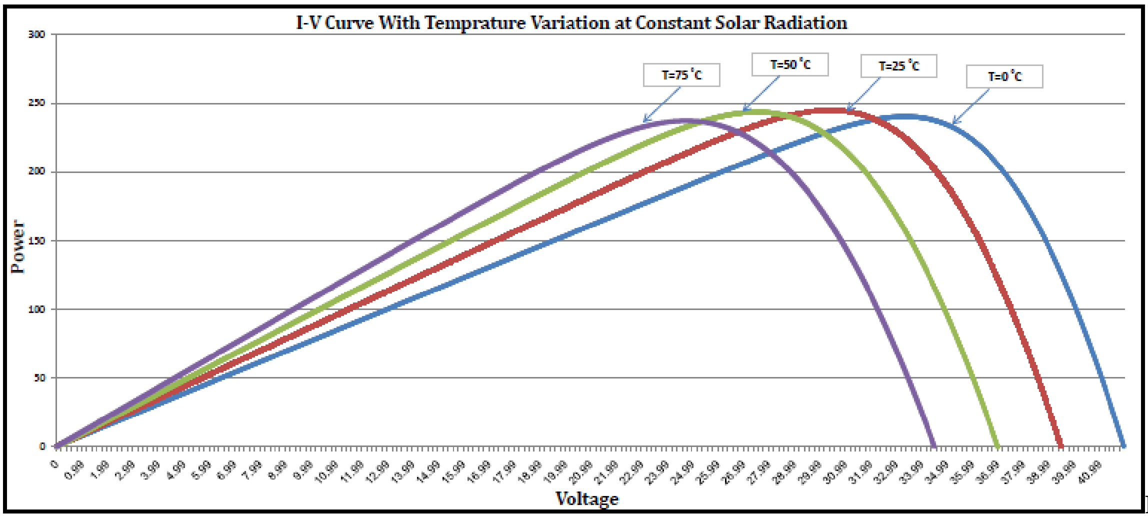


Figure 5-4 (b): P-V Curve for Temperature Variation at Constant Solar Radiation.

5.2.2 Variation of Solar Radiation

Figures 5-5 shows the impact of solar radiation variation on the PV cell's characteristic curve at constant temperature. An increase in solar radiation causes the output current to increase and the horizontal part of the curve moves upward, leading to an increase in the power output.

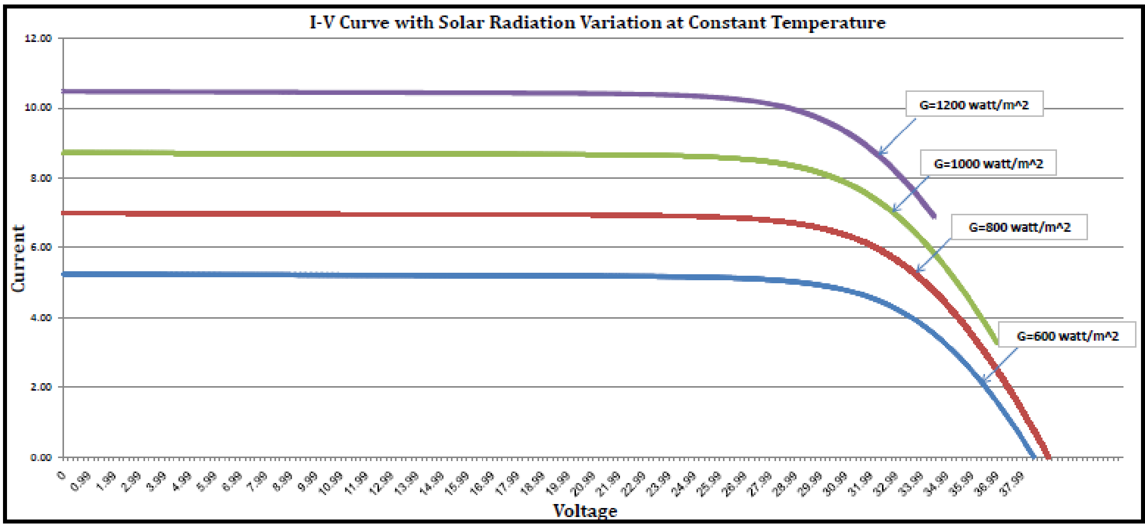


Figure 5-5 (a): I-V Curve for Solar Radiation Variation at Constant Temperature.

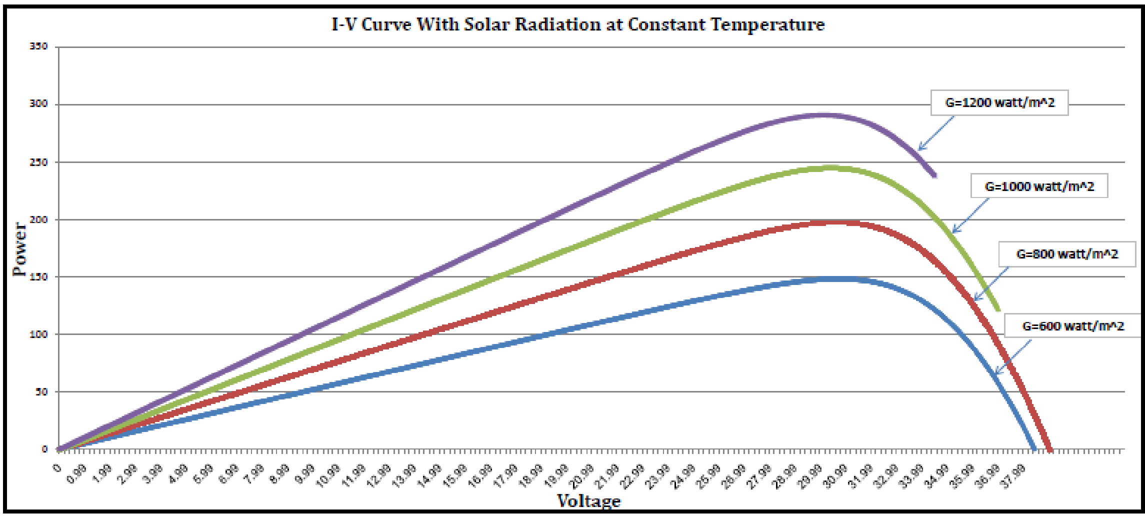


Figure 5-5 (b): P-V Curve for Solar Radiation Variation at Constant Temperature.

Although both parameters had an impact on the PV cell's characteristic curves and influenced the output power, the variation of solar radiation had a more effective influence. Doubling the solar radiation from 600 watt/m^2 to 1200 watt/m^2 led to an increase in PMPP approximately the double (figure 5-5(b)), where a double in temperature from 25°C to 50°C led to a slight decrease in the PMPP (figure 5-4(b)). Solar radiation has a higher priority for picking the location of the PV power plant.

An operating point of a photovoltaic module will move by varying solar radiation, cell temperature, and load values. For a given solar radiation and operating temperature, the output power depends on the value of the load. As the load increases, the operating point moves along the curve towards the right. There is only one load value produces a PV maximum power. The maximum power points line, which is positioned at the knees of the I-V curves, has a nearly constant output voltage at varying solar radiation conditions. When the temperature varies, the maximum power points are generated in such a manner that the output current stays approximately constant.

5.3 Comparison Between PV Performance at Different Locations

A location would differ from one to other in two environmental parameters; temperature and solar radiation. Hurghada and Cairo were the two locations picked to accommodate the PV system. The temperatures for each were collected and the solar radiations were calculated using equations (3-17) – (3-23), per hour for a year. Figures 5-6 shows the two locations' hourly temperature variation during the year and figures 5-7 shows their hourly solar radiation variation during the year.

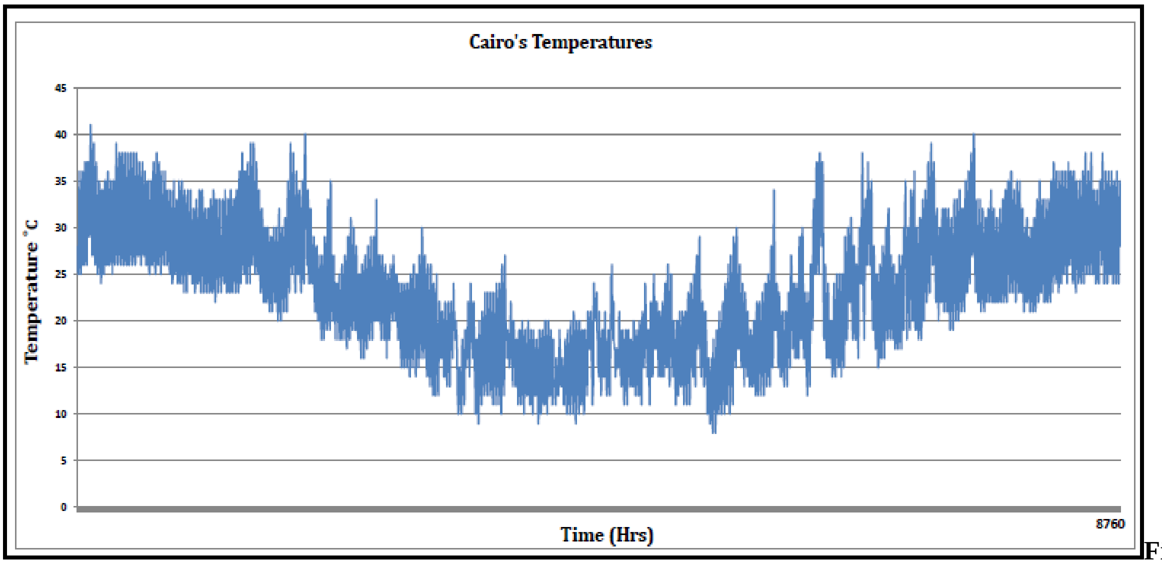


Figure 5-6 (a): Hourly Temperature Variation in Cairo for 1 year.

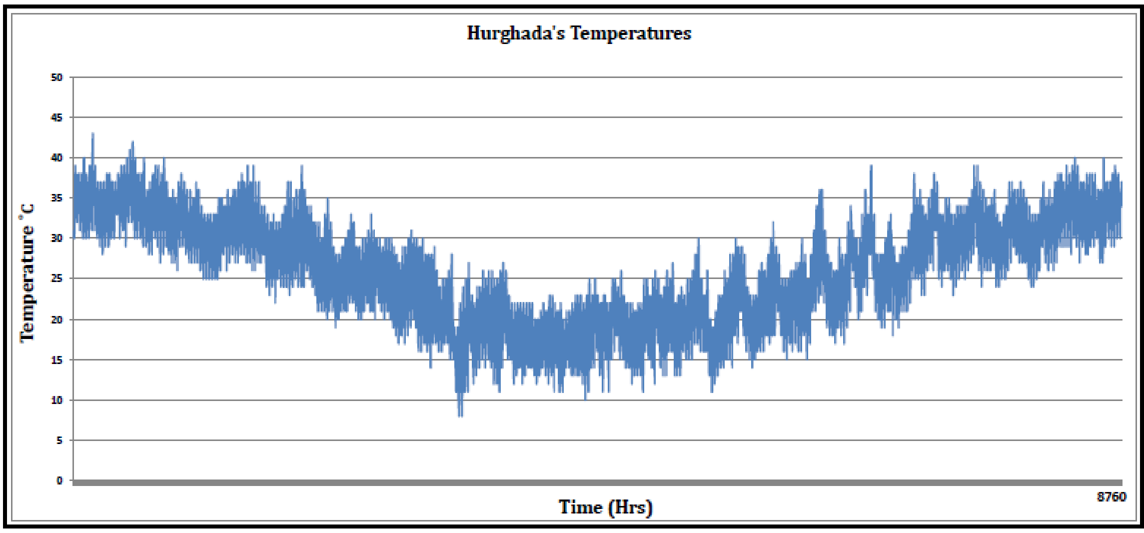


Figure 5-6 (b): Hourly Temperature Variation in Hurghada for 1 year.

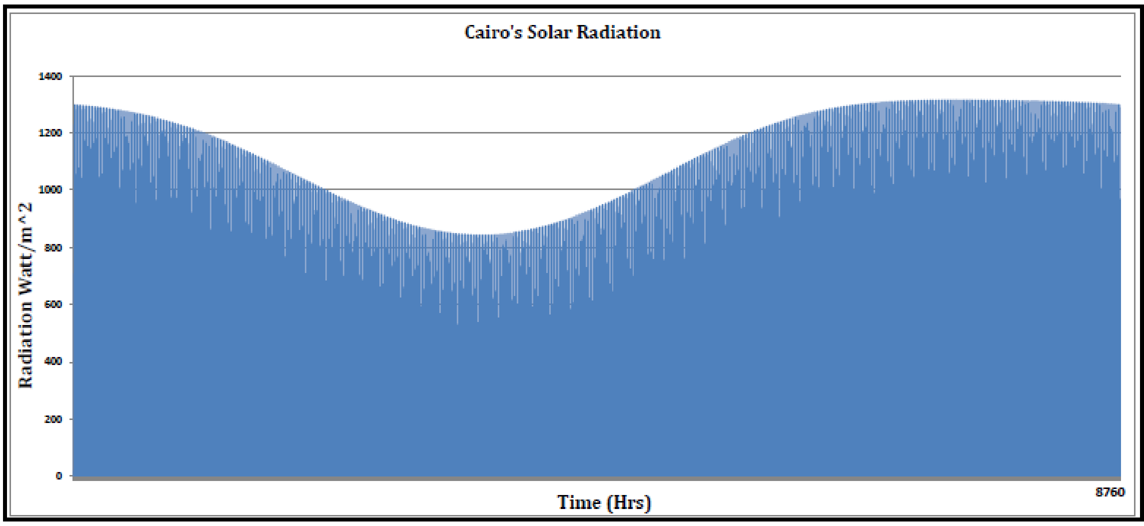


Figure 5-7 (a): Hourly Solar Radiation Variation in Cairo for 1 year.

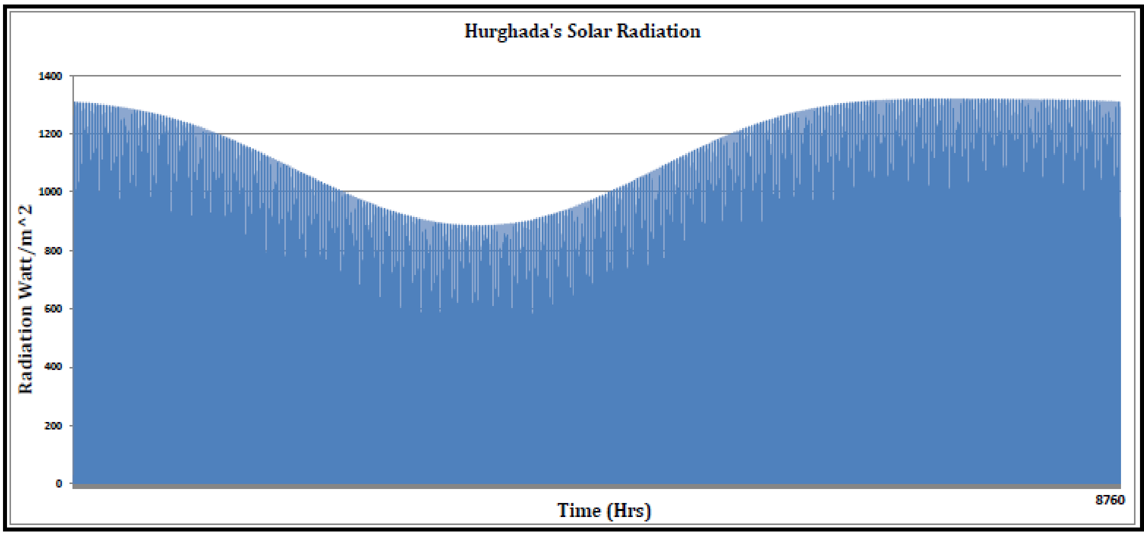


Figure 5-7 (b): Hourly Solar Radiation Variation in Hurghada for 1 year.

As mentioned previously, the solar radiation has a more effective impact on the power output of the PV module; figure 5-8 and table 5-1 compare the monthly maximum solar radiation for each location. It is observed that Hurghada has a higher solar radiation throughout the year.

Location \ Month	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11
Hurghada	1307.08	1259.99	1151.33	1006.14	903.69	984.66	1118.79	1247.13	1306.84	1318.46	1318.45	1316.05
Cairo	1297.28	1244.80	1130.40	977.00	865.62	943.09	1083.53	1225.15	1297.04	1314.51	1314.61	1311.01

Table 5-1: Monthly Maximum Solar Radiation for Cairo and Hurghada.

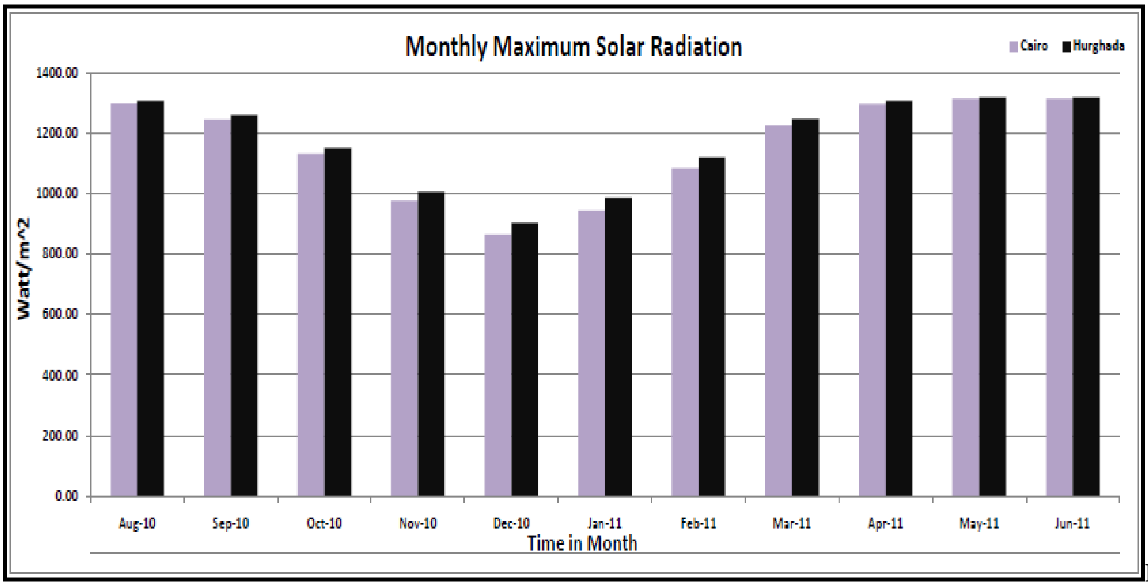


Figure 5-8: Monthly Maximum Solar Radiation for Cairo and Hurghada.

5.3.1 Performance of PV system during the four seasons

Figures 5-9 compares the AC power output of the PV system in the two locations during each of the four seasons.

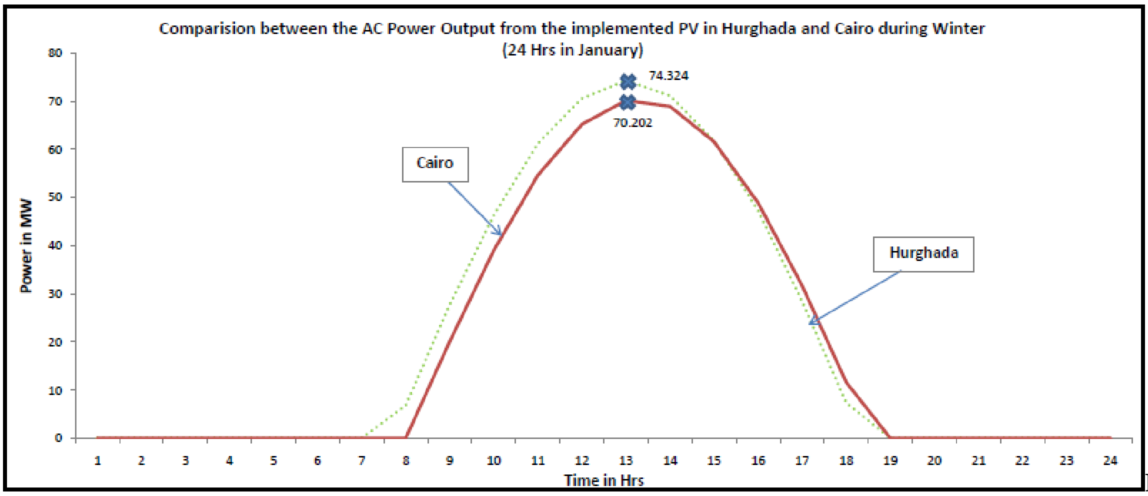


Figure 5-9(a): Comparison between PV Systems in Cairo and Hurghada During Winter.

During the winter season, the number of output power hours is the least for both locations, approximately 11hours for Cairo and 12 hours for Hurghada. The maximum power for Hurghada is 74.524 MW higher than that 70.202 MW for Cairo. The least power output for the PV module is obtained in the winter due to the shorter sunlight hours and clouds, not due to the cold temperature.

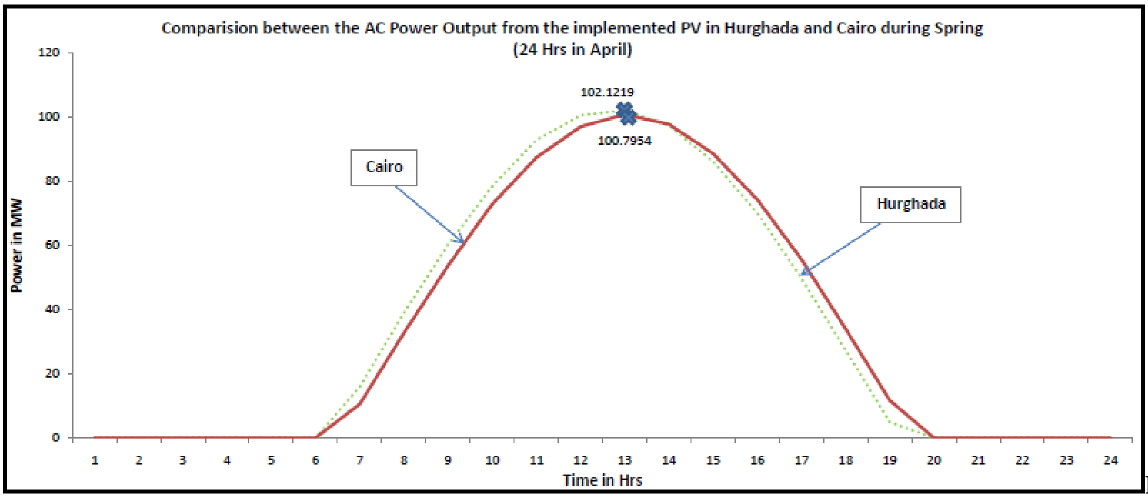


Figure 5-9(b): Comparison Between PV Systems in Cairo and Hurghada During Spring.

Later in the year, during the Spring season, the number of hourly output power is extended for Cairo and Hurghada to be approximately 14 hours for each. However, Hurghada's maximum power is higher than Cairo's, 102.1219 MW and 100.7954 MW respectively. This is due to the higher solar radiation available in Hurghada.

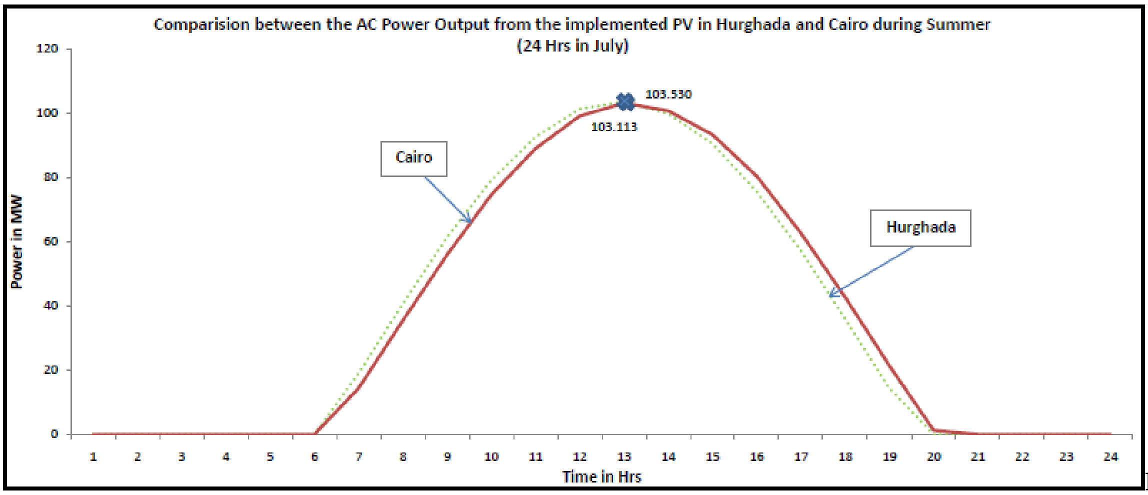


Figure 5-8 (c): Comparison Between PV Systems in Cairo and Hurghada During Summer.

Moving into the Summer season, the power output increase to its maximum value during the year, 105.55 MW for Hurghada and 103.113 MW for Cairo. This is due to the higher solar radiation during the summer period and longer length of daylight, extending the number of output power hours to approximately 14 hours for both locations.

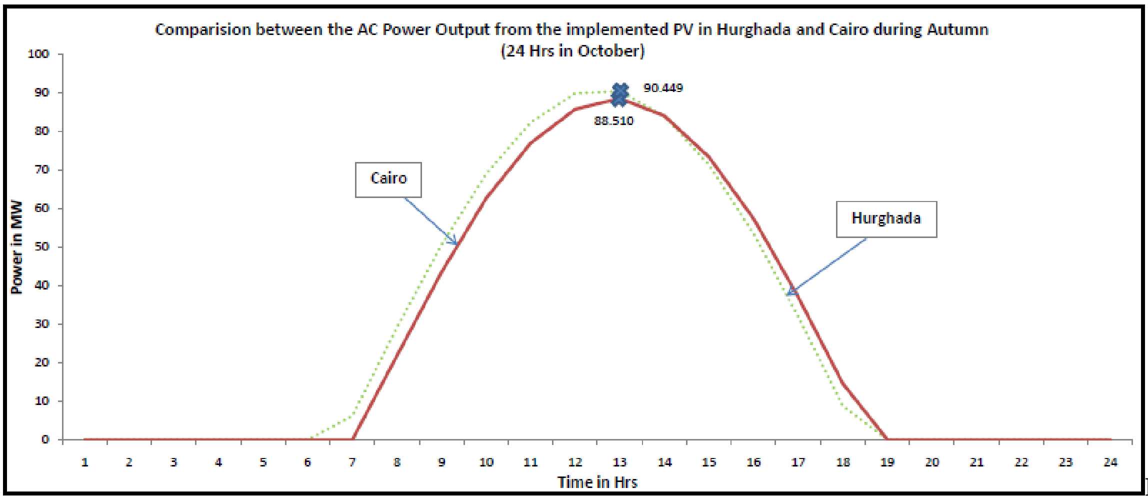


Figure 5-8(d): Comparison Between PV Systems in Cairo and Hurghada During Autumn.

Finally in Autumn, the output power is obtained for 13 hours in Hurghada and 12 hours for Cairo. Hurghada remains to supply higher power than Cairo; 90.449 MW and 88.51 MW respectively.

The PV power is to be fed into the utility grid to supply all needed loads in Egypt. Figure 5-10 shows the hourly recorded total load that needs to be supplied during a year.

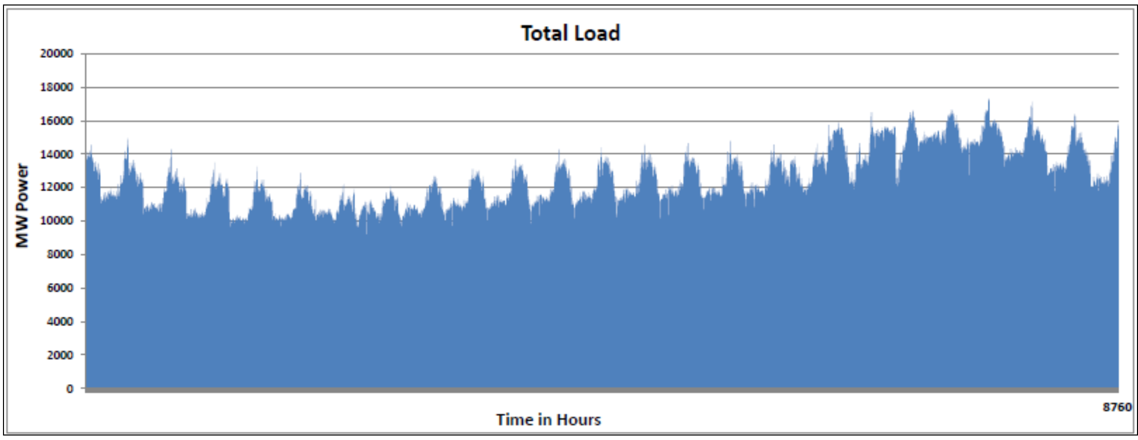


Figure 5-10: Hourly Total Load for 1 year.

The PV power plant is designed to generate 140MW, and is virtually located once in Cairo and once in Hughada to study its performance. The power output of each was added to the total generation of the utility grid at a time. Figures 5-11 shows the AC output power of the PV in the two locations for 48 hours during the Summer compared to the load. Although the difference in output power is not significant between the two locations, yet when compared to the load, a service interruption was observed. In figure 5-11(a) the total load is supplied for the 48 hours for both Cairo and Hurghada with no service interruptions. Whereas in figure 5-11(b), the total load is fully supplied only by Hurghada and service interruptions were valid by Cairo.

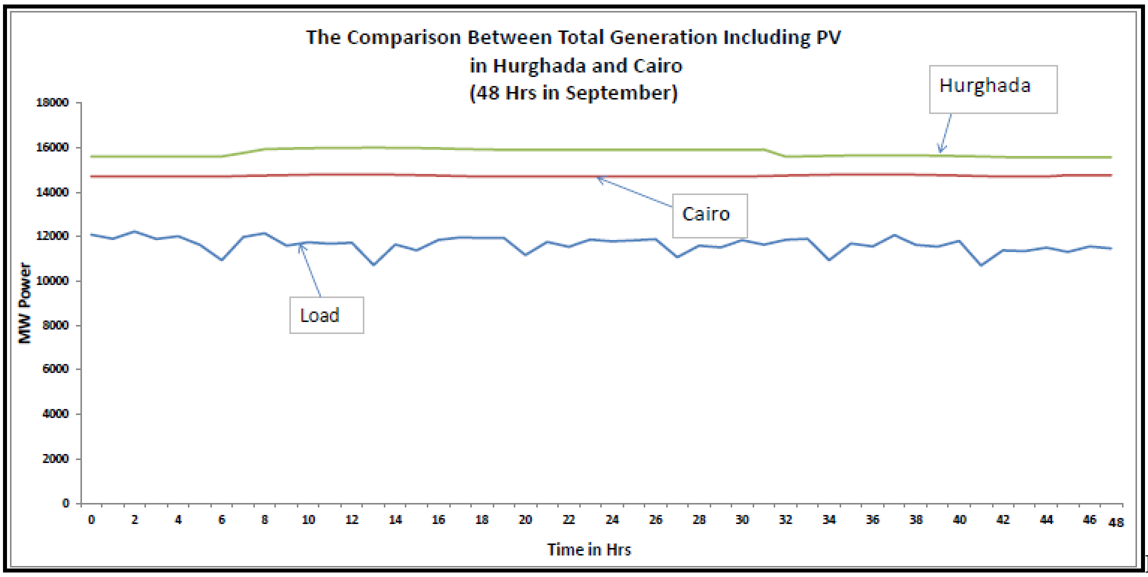


Figure 5-11(a): Comparison Between Total Generation with PV implemented in Cairo and in Hurghada with Total Load Fully Supplied for 48 hours in September.

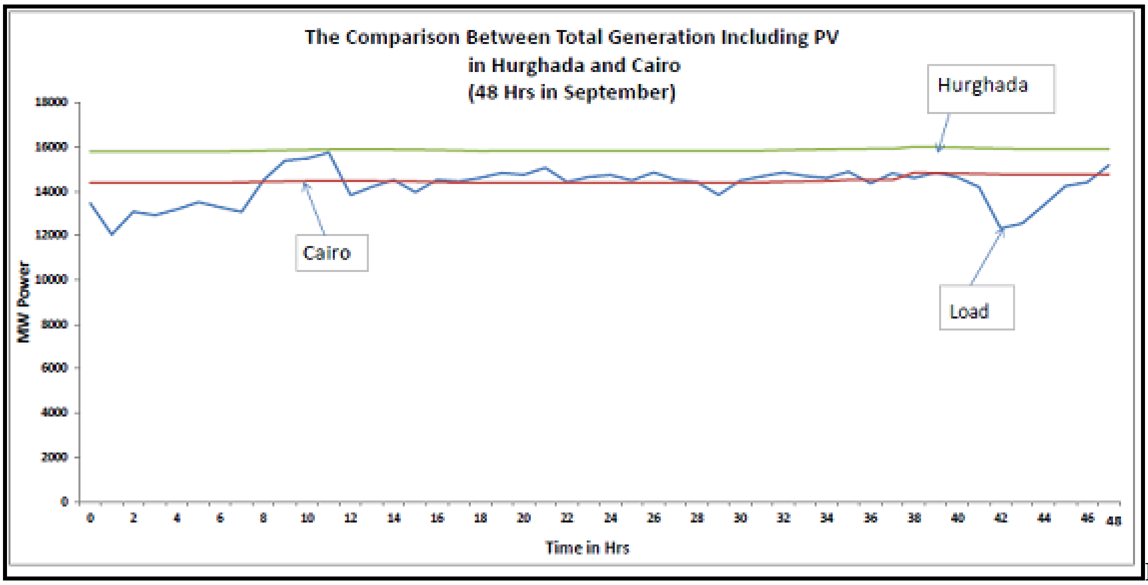


Figure 5-11(b): Comparison Between Total Generation with PV implemented in Cairo and in Hurghada with Total Load Not Fully Supplied for 48 hours in September.

It can be concluded that accommodating the PV power plant in Hurghada will be more efficient than Cairo due to having higher solar radiation throughout the year, leading to more power generation. Further studies were carried out to study the reliability of locating the PV power plant in Hughada under different cases.

5.4 Reliability Performance of Grid-Connected PV System During Load Increase

A 140MW PV plant was virtually located in Hurghada and connected to the utility grid and load as modeled in chapter 4. Reliability studies were carried out to measure the performance of connecting the PV and its impact. The Three indices (LOLE, LOEE and LOLF) previously discussed in chapter 4 where calculated according to equations 4-1 to 4-3. Figures 5-12, compares for each index, the performance with and without connecting the140MW PV plant during the basic load and during 5%, 10% and 15% increase in load.

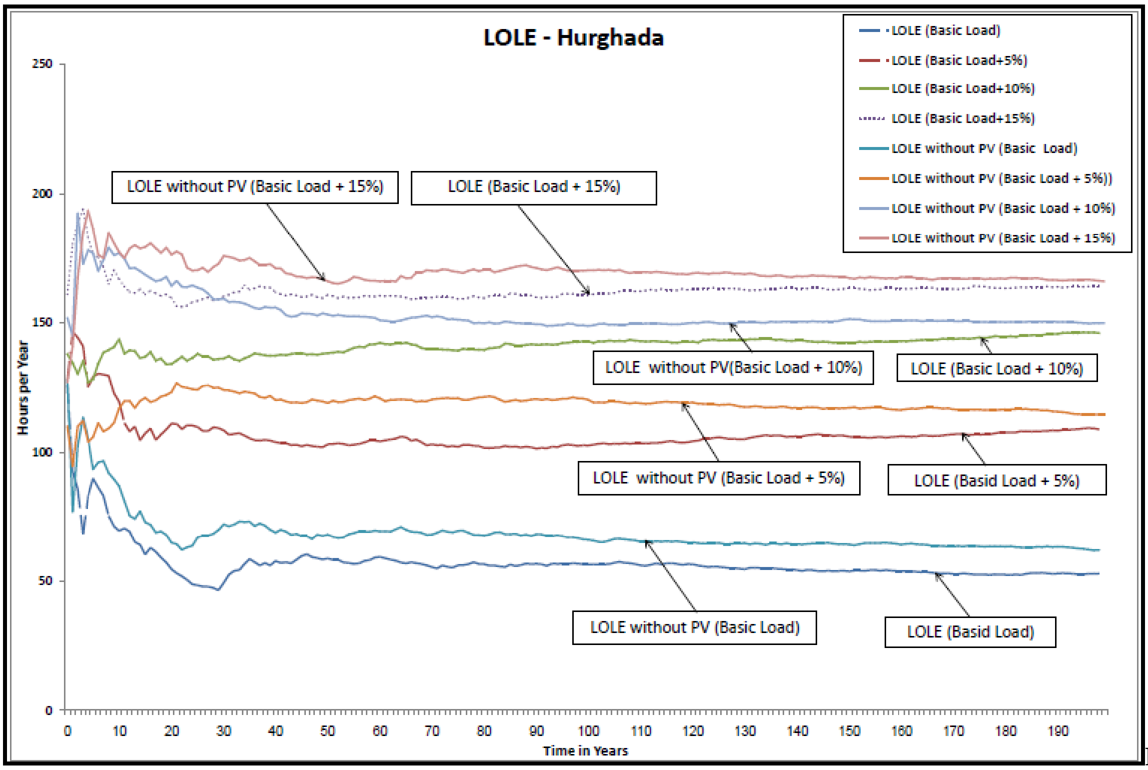


Figure 5-12 (a): LOLE During an Increase in Load.

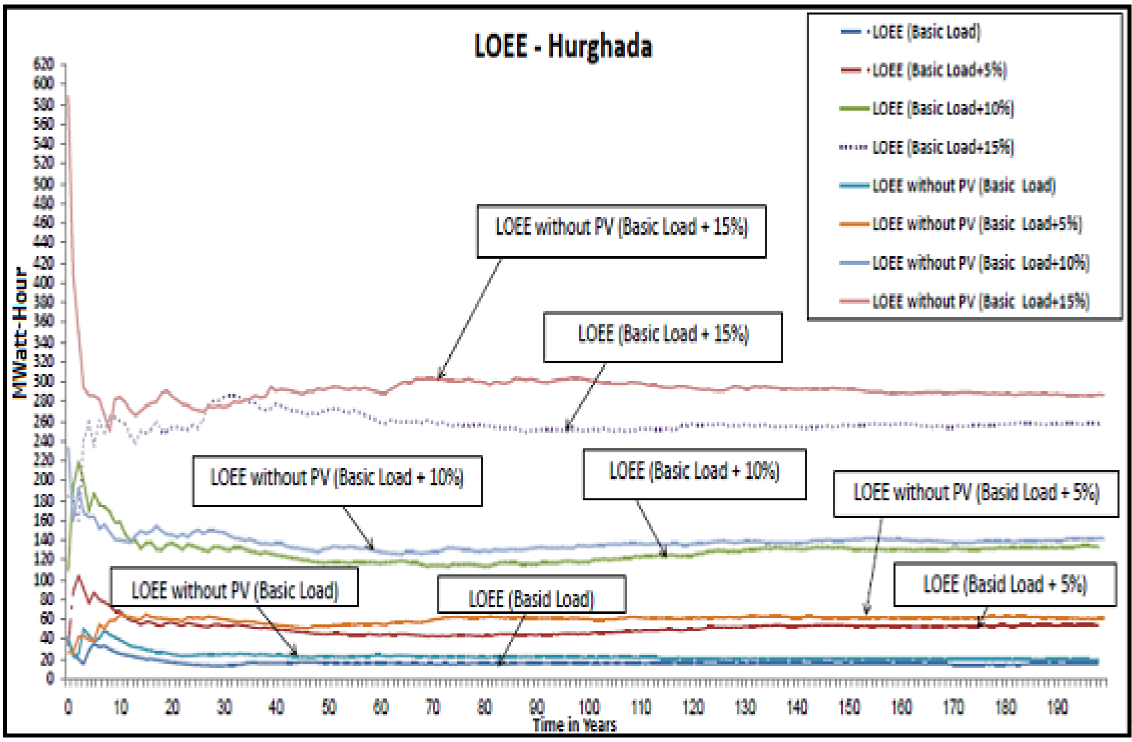


Figure 5-12 (b): LOEE During an Increase in Load.

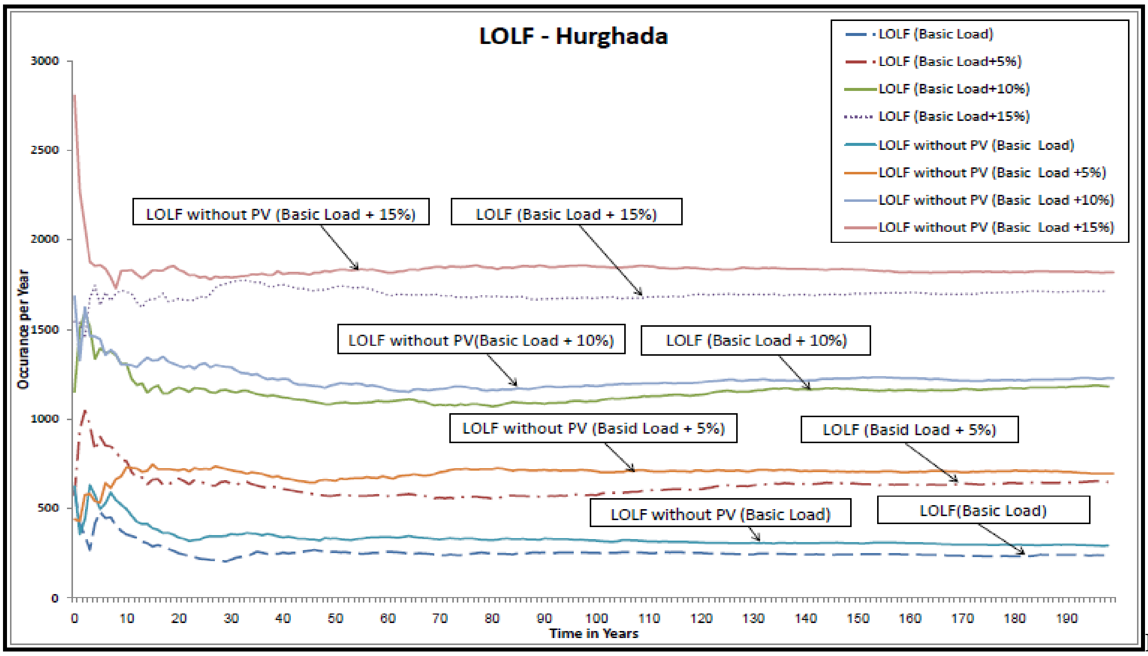


Figure 5-12 (c): LOLF During an Increase in Load.

Figures 5-12 (a), (b) and (c), show the LOLE and LOEE and LOLF respectively as a comparison between the connection of the PV to the total generation and the total generation alone for each of the four cases. The first case was for the basic load, the second case was for a 5% increase in the load, third case was for 10% increase in load and finally, for a 15% increase in load. It was found that for all cases, the addition of PV to the grid had a positive impact as a decrease in each index was observed. Table 5-2 shows the calculated percentage decrease in each case for each index.

Increasing the total power generation by the addition of 140MW PV Plant has decreased the number of interruptions (LOLF), the amount of load not being supplied (LOEE) and the duration of the interruption (LOLE). As the load increases, a positive impact can still be gained by the PV addition, but with less influence.

Case	**Reliability indices**		
	LOEE	***LOLE***	***LOLF***
Basic load	21.5%	15.3%	18.2%
Basic load + 5%	12.36%	5.2%	7.29%
Basic load + 10%	6.06%	2.55%	3.78%
Basic load + 15%	4.71%	1.28%	1.27%

Table 5-2: Percentage decrease in Reliability Indices Caused by PV Implementation at Different Loads.

5.5 Reliability Performance for the Addition of the PV Power Plant through Different DC to AC Derate Factors

As mentioned previously in chapter 3, the PV plant generates DC power which needs to be converted into AC power with the means of an inverter to be fed into the grid. This could be calculated through an DC to AC derate factor as in equation 3-19. The DC to AC derate factor compensates for the presence of the inverter. The default derate factor used was 77%. The derate factor was increased to 85% and reduced to 60% to study its impact on the reliability indicies. Figures 5-13 (a), (b) and (c) show the effect of varying the derate factor on LOLE, LOEE and LOLF respectively.

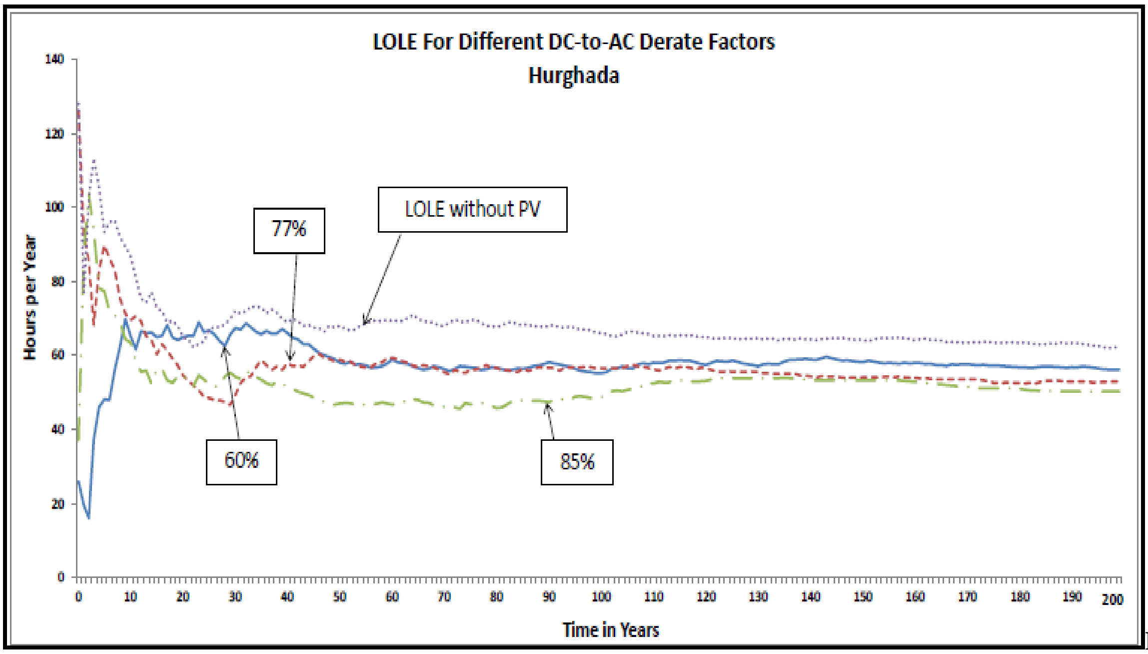
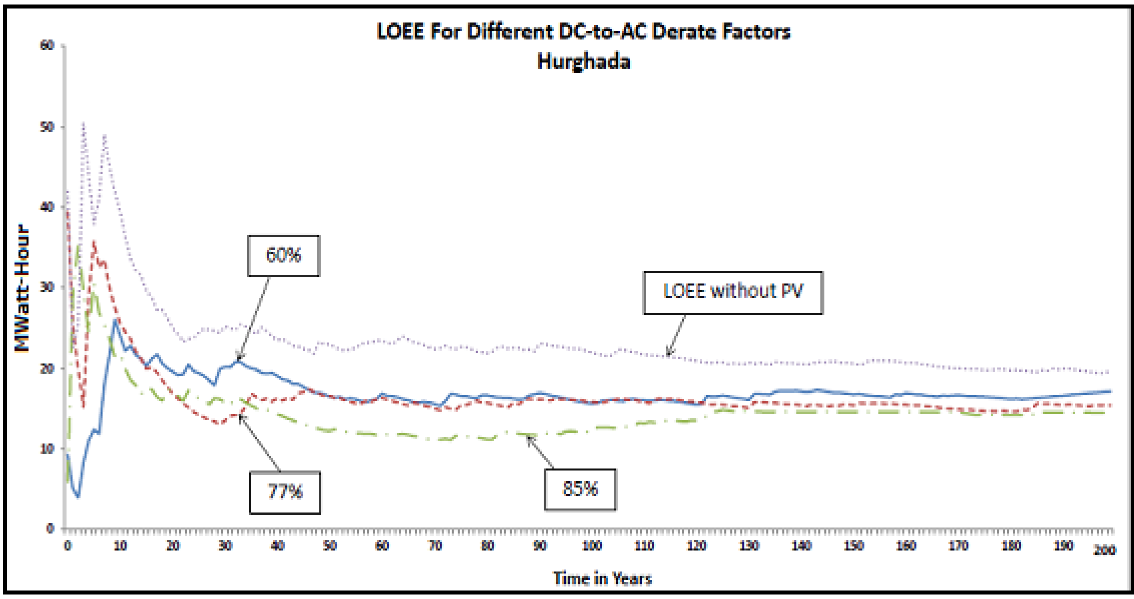


Figure 5-13 (a): LOLE for the Addition of PV Through Different DC to AC Derate Factors.



**Figu
re 5-13 (b): LOEE for the Addition of PV Through Different DC to AC Derate Factors.**

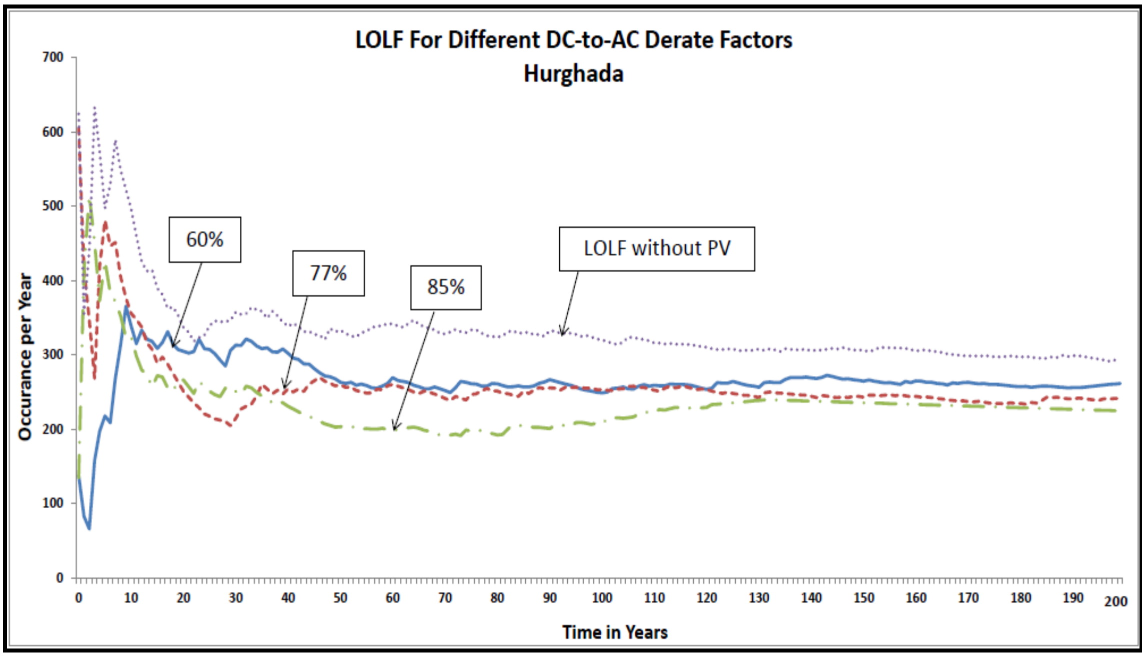


**Fig
ure 5-13 (c): LOLF for the Addition of PV Through Different DC to AC Derate Factors.**

It was observed that increasing the derate factor, caused a reduction in each of the reliability indices, while decreasing it caused an increase. This is because the derate factor is taken as a percentage of the PV output power. The higher the percentage, the more power is injected into the grid and serving more loads. Thus, increases in the DC to AC derate factor leads to better performance and less service interruptions.

Table 5-3 presents calculated percentage decrease in each of the reliability indices corresponding to the derate factor used. These percentages are based on a comparison between the performance obtained using each derate factor with the performance of the grid disclosing the PV generation. It is observed that increasing and decreasing the derate factor than the default value (77%) still contributes with a positive impact. However, decreasing it would lead to more frequent service interruptions, for longer duration and loss of greater loads.

DC-to-AC Derate Factor	**Reliability indices**		
	LOEE	***LOLE***	***LOLF***
60%	12.8%	11.02%	11.26%
77%	21.66%	15.07%	22.26 %
85%	26.3%	19.5%	23.7%

Table 5-3: Percentage decrease in Reliability Indices Caused by PV Implementation at Through Different DC-to-AC Derate Factors.

5.6 Reliability Performance for the Substitution of Conventional Generating Units with Equivalent Capacity of PV Generation

The Grid consists of a number of conventional generating units. A 140MW PV plant was virtually connected to the grid increasing the total generation, where an equivalent capacity of 140MW of conventional generating units was disconnected from the grid. Reliability studies were then carried out to observe the influence of the addition of PV generation over that of same capacity conventional gas generation.

Figures 5-14 (a), (b) and (c) compares the total generation without PV contribution, to the total generation with 140MW PV contribution, to the total generation with 140mW PV contribution after disconnecting 140MW of the gas generation, for each of the reliability indices.

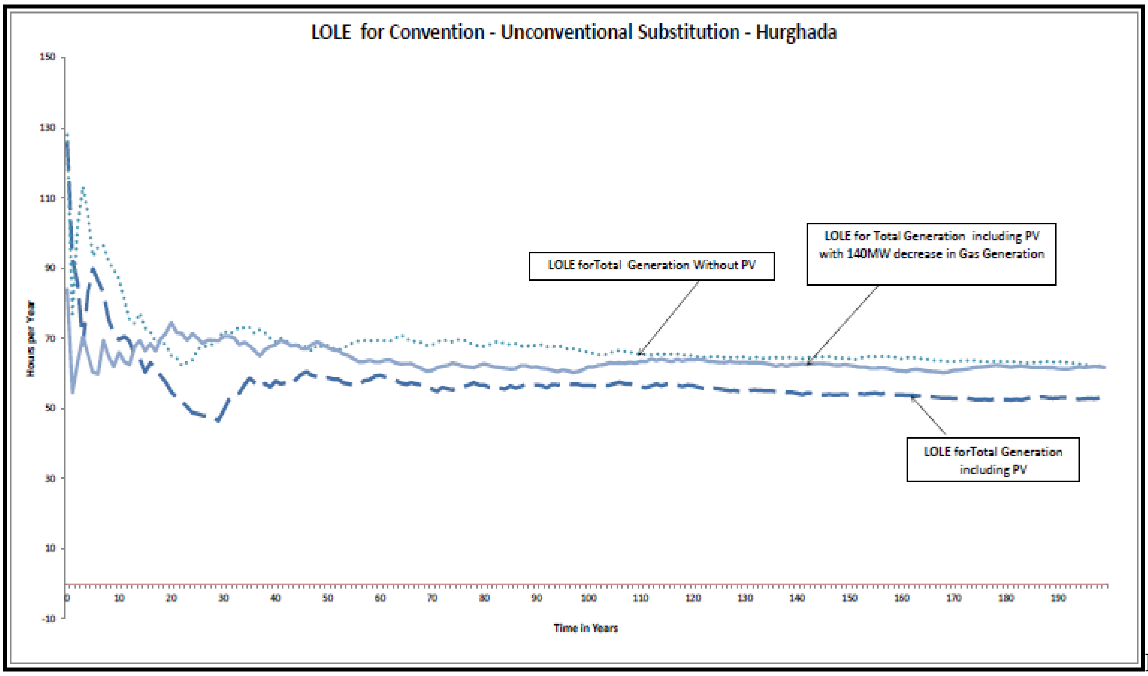


Figure 5-14 (a): LOLE for Conventional-Unconventional Equivalent Capacity Substitution.

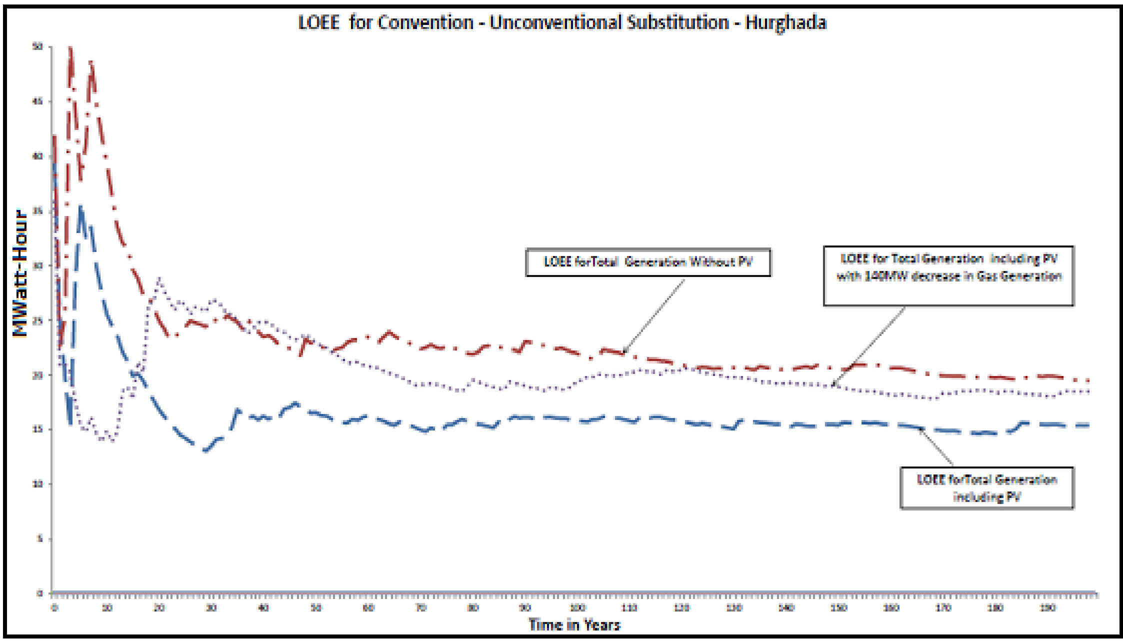


Figure 5-14 (b): LOEE for Conventional-Unconventional Equivalent Capacity Substitution.

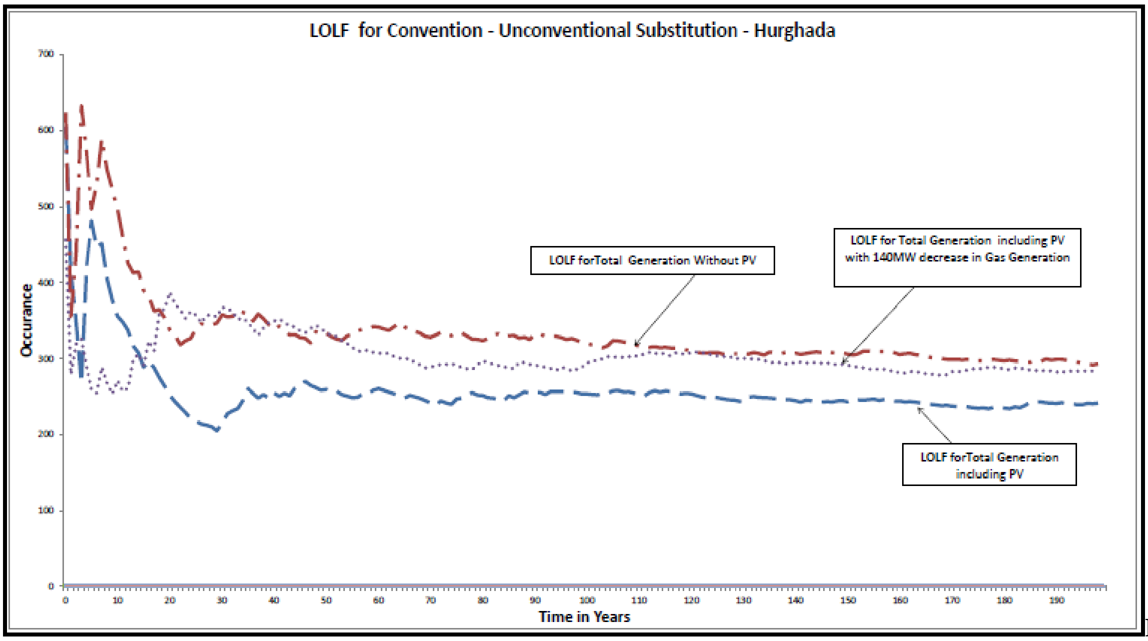


Figure 5-14 (c): LOLF for Conventional-Unconventional Equivalent Capacity Substitution.

As expected, the total generation including the PV power gave best results for it having the greatest amount of generation. The contribution of gas generation and PV generation was approximately similar, yet PV's contribution was more positively effective. This would promote the idea of implementing more PV plants to the utility than implementing gas plants.

Chapter Six

6 CONCLUSIONS & FUTURE WORK

6.1 Conclusions

This thesis investigated the reliability impact of connecting a photovoltaic system to a large electrical network; the Unified electrical Network of Egypt. This was achieved through a proposed novel PV model that is based only on datasheet values. The PV model was extended to be suitable for reliability studies and contributed as part of the electrical power system of Egypt. Actual data was taken from the national grid; MTTF, MTTR and rated power, which were used to model the conventional generators using state duration approach. Besides, the load demand was simulated using actual data taken from the national grid as well. The whole model was implemented on Matlab® software package. The impact of the PV plant on the power system's reliability was studies and carried out through three main indices, including and disclosing the PV contribution.

The novel simulated PV model was a positive contribution for the following:

- The PV model was verified using three different types of PV module datasheets, where no assumptions need to be considered. The characteristic curves; I-V and P-V were obtained and showed excellent correspondence to the manufacturer's published curves.
- Two environmental parameters were varied; temperature and solar radiation, to show their effect on the characteristic curves that matched those previously discussed in chapter 3.
- The model is capable of accommodating any location in the world, as it receives inputs of hourly temperature and solar radiation.

The PV plant was located virtually in two locations in Egypt; Cairo and Hurghada to compare its performance. Hourly temperatures were collected for the two locations, and hourly solar radiation levels were calculated for each using a mathematical model. Due to Hurghada's great solar radiation level, more power output was obtained. Hurghada was picked to accommodate a 140 MW PV plant which was connected to the Unified Electrical Network of Egypt for further reliability studies.

Reliability studies were carried out for a long simulation period using Monte Carlo Simulation Approach. The impact of connecting the PV system to the grid was observed through three reliability adequacy indices; LOLE, LOEE and LOLF. Each index was calculated during both integrated and non-integrated PV systems with the grid. Four cases were tested and results showed the following:

- Using the basic load recorder from the grid, the power system including the PV power plant preformed better than that without the PV generation. A reduction of 21.5% for LOEE, 15.3% for LOLE and 18.2% for LOLF was observed.
- The load demand was increased by 5%, and the PV integrated system showed better reliability performance than that without PV. A reduction of 12.36% for LOEE, 5.2% for LOLE and 7.29% for LOLF was observed.
- The load demand was increased by 10%, and the PV integrated system showed better reliability performance than that without PV. A reduction of 6.06% for LOEE, 2.55% for LOLE and 3.78% for LOLF was observed.
- Moreover, the load demand was increased by 15%, and the PV integrated system showed better reliability performance than that without PV. A reduction of 4.71% for LOEE, 1.28% for LOLE and 1.27% for LOLF was observed.
- The results showed that integrating the PV system to the grid has a positive impact, but decreases with an increasing load. This is expected, since the total generation is stable with no corresponding increase.
- The DC to AC factor was varied in the PV model. It was decreased to 60% and increased to 85% , then compared to the 77% default used value as well as the power system disclosing the PV plant. Best performance was obtained for a DC to AC factor of 85%, followed by the 77% then the 60%. However, PV integrated power

systems showed to be more reliable than those without. Table 5-3 compares the results for each.

- A 140 MW of conventional generation was disclosed from the large electrical network corresponding to 140 MW PV generation enclosures. Reliability indices showed a better performance during the integrated 140 MW PV power than during the 140 MW conventional generations.

PV power plants are of a great contribution to the Unified Electrical Network of Egypt. The results showed a better performance during the PV integration, where the power system becomes more reliable, capable of supplying more demand with less outages. PV power plants are environmentally friendly and safe, which helps in decreasing the available pollution. Overall, photovoltaic power generation is one of the optimum choices that need to be considered to increase the country's generation and increase its reliability, in order to cope with rapid population and electrical demand.

6.2 Future Work

Based on the research presented in the thesis, more studies could be carried on in the future, some of which are:

- The PV model could be improved by adding to it shading and wind speed considerations.
- Maximum power point tracker (MPPT) could be added to the model to increase the PV output power.
- Further reliability studies could be carried out on stand-alone PV system.
- Further reliability studies could be carried out on a hybrid system contain the PV and other sources of renewable energy, such as wind.
- Power Quality of PV connected power system could be investigated.

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APPENDICES