KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

PROJECT REPORT ON

STUDY ON THE TECHNICAL CHALLENGES AND IMPACT OF INTEGRATING HIGH PENETRATION PHOTOVOLTAIC (PV) SYSTEMS INTO THE GHANAIAN TRANSMISSION GRID

BY

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A THESIS SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING, KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

JULY, 2013

DECLARATION

I hereby declare that this submission is my own work towards the MSc. and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

26 /05/2014

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ABSTRACT

Growing concerns about energy security, the sky rocketing prices of fossil fuels and greenhouse gas emission control have heightened interest in the harnessing of renewable energy resources in response to these critical issues. However, the integration of high shares of renewable energy such as Solar Photovoltaic into the electrical transmission grid brings with it a host of technical challenges. The lack of understanding and technical know-how to resolve these challenges has preempted the development of renewable energy in many countries, especially in Africa.

The inherently intermittent nature of renewable energy sources poses operational, efficiency and reliability challenges to current power systems due to temporal fluctuations, geographical dispersion of renewable energy sources and inadequacy of the existing power grid. This research focused on the technical challenges and impact associated with the integration of high scale Solar PV on the Ghanaian transmission grid and provides systemic solutions and standards necessary for the successful integration of large share Solar PV systems. The research undertook the modeling and simulation of 2.0 MWp PV of the Volta River Authority's Renewable Energy Development. The simulated results at various penetration levels for voltage, power losses and total harmonic distortion are presented and analyzed.

It can be concluded from the simulated results and analysis that the injection of high penetration solar PV causes a voltage rise, which is directly proportional to the penetration level. Further, there is a decrease in total power losses and an increase in total harmonic distortion at all penetration levels.

Key-words: Technical challenges, Solar PV, Penetration level, Integration

ACKNOWLEDGEMENTS

I am thankful to God for the wisdom, grace and kindness He has extended to me throughout this project. Were it not for His gracious guidance, this work would not be what it is. My thanks also go to my supervisor, Mr. Emmanuel K. Anto, for his support, matured counsel and guidance throughout this project.

I must equally acknowledge the late Prof. Abeeku Brew-Hammond who inspired and encouraged my interest in renewable energy and in this MSc. program. I also thank my program coordinator and assistant program coordinators, Dr. Gabriel Takyi and Dr. Lena Mensah / Mr. David Ato Quansah respectively, for their support. Mr. Kwame Osae of Volta River Authority also deserves special mention and thanks for furnishing me with data from the VRA project which formed the basis of my modeling and simulations.

DEDICATION

This work is dedicated to the late Prof. Abeeku Brew-Hammond, who served as Director of the Energy Center at Kwame Nkrumah University of Science and Technology (KNUST). His passion for and commitment to renewable energy work inspired my own vested interest in the field. In many ways he was a mentor, counsellor and father figure to me. He will be dearly missed.

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ABBREVIATIONS

PV	Photovoltaic
RE	Renewable Energy
REDP	Renewable Energy Development Project
NREL	National Renewable Energy Laboratory
GE	General Electric
WWSIS	Western Wind and Solar Integration Study
IEEE	Institute of Electrical and Electronic Engineering
SVC	Static Var Compensator
STATCOM	Static Synchronous Compensator
CAISO	California Independent System Operator
LV	Low Voltage
MV	Medium Voltage
MSB	Market Strategy Board
IEC	International Electrotechnical Commission
GHG	Greenhouse Gas
IEA	International Energy Agency
VRA	Volta River Authority
TAQA	Abu Dhabi National Energy Company
IPP	Independent Power Producers
DC	Direct Current
AC	Alternating Current
STC	Standard Test Conditions
OpenDSS	Open Distribution System Simulation

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

In 2011, global investment in the renewable energy sector hit a record of $257 billion which was 17% up from the 2010 figure. This was a six fold increase on the 2004 figure and 93% higher than the total in 2007, the year before the world financial crisis. The use of renewable energy sources to generate electricity expands significantly in all three scenarios modeled by the World Energy Outlook. In the New Policies Scenario, renewable-based electricity generation worldwide almost triples, from 3 900 TWh in 2009 to 11 100 TWh in 2035. This expansion is driven largely by government policies, including subsidies, and represents 44% of the growth in total electricity generation over the period. [1][2]

More specifically, solar PV electricity generation increases substantially over the Outlook period, from 20 TWh in 2009 to 740 TWh in 2035 in the New Policies Scenario, growing at an average rate of 15% per year. The European Union accounted for three-quarters of global solar PV generation in 2010. This has been driven by strong government programs, particularly in Germany where there has been rapid growth in recent years. Over the early years of the Outlook period, Europe continues to exhibit very strong growth in solar PV generation but, between 2020 and 2035, the increase in solar PV generation in each of China, the United States and India is larger than that in the European Union. [2]

Given the growing concerns about energy security, sky rocketing price of fossil fuel and greenhouse gas emission control, an initiative to get a cleaner and uninterrupted power supply to augment the existing Ghanaian capacity could not be more timely. Current literature has clearly established the relationship between energy consumption and economic growth: it will be difficult to attain the better Ghana agenda with poor energy production and delivery. It is in recognition of this challenge that the overall national renewable energy policy target is to attain 10% Renewable Energy in the national energy mix by 2020. [3]

The institutional framework has already been setup for the development of renewable energy resources in Ghana. The Parliament of the Republic of Ghana passed the Renewable Energy Bill into Law, thus Renewable Energy Act 2011 (Act 832) which has a feed-in tariff component and a provision for the establishment of a renewable energy fund. The law also grants Independent Power Producers the privilege to integrate their large share renewable energy generation on the national grid system.

According to the Law 30 (1), "An operator of a transmission or distribution system shall connect a generator of electricity from renewable energy sources within the coverage of the transmission or distribution system where a generator of electricity from renewable energy sources so requests." This opportunity has heightened the interest of both national and international investors in Ghana's renewable energy sector, with Mere Power Nzema Limited taking the lead by building Africa's largest solar PV power plant (155MW) at Aiwiaso in the East Nzema district of Ghana. [4]

1.2 Problem Statement

Ghana is endowed with enormous solar energy resources spread across the entire country. Daily solar irradiation levels range from 4kWh/m2 to 6kWh/m2. As earlier noted, the necessary institutional framework for the development of renewable energy in the country has already been established. However, high penetration of solar PV is bound to have a significant impact on the transmission grid; a lack of widespread understanding of the technical implications of solar PV integration is stunting the development of renewable energy projects in many countries, including Ghana. Moreover, there hasn't been any similar research work on the technical challenges and impact of the integration of high penetration of Photovoltaic (PV) systems into the Ghanaian transmission grid.

1.3 Justification

The intermittent nature of Solar PV sources poses operational efficiency and reliability challenges to power systems due to temporal fluctuations, geographical dispersion of renewable energy sources and inadequacy of the existing power grid. The successful connection of equipment to the electrical grid requires that basic power quality requirements be met for harmonics, voltage, and frequency. Renewable energy generators, with their associated power electronics, generate harmonics and have electrical characteristics under voltage and frequency excursions that may make it difficult to meet those requirements. Furthermore, the variability of renewable resources, due to characteristic weather fluctuations, introduces uncertainty in generation output on the scale of seconds, hours and days. Concerns about power system reliability thus limit the amount of renewable energy that power utilities and transmission system operators allow to be connected to the grid. [5]

Large-scale PV systems integration presents a spectrum of technical challenges arising mostly from the expanding application of power electronic devices at high power ratings. The connection of renewables at the distribution levels also requires significant modification of the distribution design to accommodate bidirectional power flow. The amount of Solar PV penetration has a significant impact on the transmission systems and some cases require a huge investment in transmission expansion because of capacity. Facilitating the integration of distributed energy resources requires innovations in micro-grid and energy management systems that transparently provide control and regulation. [5]

To seamlessly integrate solar PV in the grid, research and development must intelligently address challenges that solar PV penetration levels will have on power system planning and operation. Understanding the impact and various technical challenges that large share Solar PV integration will have on the Ghanaian transmission grid will give utility and generation companies the confidence to invest in this sector.

1.4 Aim and Objectives

The main objective of this study is to investigate technical challenges and impact associated with large scale Solar PV integration into Ghanaian transmission grid.

The specific objectives of the study are to:

a) Identify the challenges that exist when integrating utility-scale Renewable Energy into transmission network system.

b) Model and simulate by means of suitable software the 2.0MWp PV of the Volta River Authority's Renewable Energy Development Project (REDP) at Navrongo at various penetration levels.

c) Make recommendations for the integration of Solar PV into the Ghanaian transmission grid.

1.5 Scope and Limitation of Study

The research study considered and reviewed literature regarding the integration of large share Solar PV into the transmission grid system. It will present the various technical challenges associated with integrating large share solar PV into the grid, based on modeling and simulation of 2.0MWp solar PV of the Volta River Authority's Renewable Energy Development Project at Nanvrogo, which would be used as a case study. The outcomes of this research are based on the limited data and information that were available.

1.6 Structure of the Thesis

The thesis is divided into seven chapters. The first chapter, the introduction outlines, the background, problem statement, justification, objectives, scope and limitation of the research study. The second chapter reviews materials relevant to the research. Chapter three outlines the technical challenges associated with integrating utility-scale Solar PV into the transmission network and development of renewable energy. Chapter four looks at Solar PV systems and grid integration theory of the research while chapter five outlines the methodology and implementation. Simulation results are analyzed in chapter six. The final chapter sums up the recommendations and conclusions of the research.

CHAPTER TWO

2.0 LITERATURE REVIEW

This chapter will focus on reviewing works relevant to this research project. Much research has been conducted on the integration of solar PV into the transmission grid. Small-scale solar PV generators have a capacity ranging from zero to 20 MW, while that of large-scale solar PV generators ranges between 100 MW and 200 MW [6] [7].

The impact of a grid-connected PV system on the steady-state operation of a Malaysian grid is presented in [8]. The main object of the research was to investigate the voltage profile and power losses of a grid connected solar PV system for residential, commercial and industrial load pattern categories at Peninsular Malaysia. After data collection, the study modeled the photovoltaic generator as a negative load connected to the distribution generation bus. The single line diagram voltages were 132 kV/11 kV. For commercial load category (> 1MW) it was discovered that the voltage increases from 6:00am to 6:00pm, but the voltage rise did not cause over-voltage when compared with the standard permissible voltage of 1.05 p.u. in Malaysia. The study also concluded that there was some substantial reduction in power losses when the solar PV was injected into the grid.

Modeling of a large grid-integrated PV station and analysis of its impact on grid voltage is reported in [9]. The paper used DIgSILENT/ Power Factory to model and simulate grid integrated solar PV. In the simulation, a 100 MW grid-connected solar PV station is connected to the grid via 500 kV line through a node, while a PV station is paralleled at another node where the voltage level is 110 kV. The power generated from the PV array is fluxed to a 10 kV bus and the voltage is boosted to 110 kV transformer whose capacity is 120MVA.

From the simulation results, it was discovered that the output of the PV station changes with the variation of temperature and irradiance in one day. Additionally, there is always a power drop for the loss about 5% in the inverter. With reference to nominal voltage, the total voltage variation range is about 0.024 p.u.

Characterization of the solar power impact in the grid was analyzed in [10] to predict the response at various penetration levels on the grid. For a more realistic approach, existing installation (1.06 MWp) was used for the studies to create new modules for solar power series.

The study used Markov Matrices to simulate series. Three penetration scenarios were carried out in this study, namely 5MWp, 10MWp and 15MWp for different seasons and during day and night. The studies concluded that additional injection of solar PV into the grid affects voltage at all the buses. For 15 MWp penetration in the month of August, which could be the most critical case, the network was able to accommodate the penetration, hence the conclusion that the Belgian grid is able to accommodate solar PV power until 15 MWp at least. Studies for higher penetration levels were recommended.

In Europe, the High Penetration of very large scale PV Systems into the European Electric Network was reported in [11]. In EU 2020 projected power generation mix of 87 GW of PV installed capacity (25 GW installation in North Africa imported in the EU grid and 50 GW of installed capacity distributed among the EU countries). Using Matpower v4.0 (a suite of MATLAB) simulation was done to investigate the effect of increased PV power generation in the European high voltage transmission network. Cross-border parallel-interconnected nodes were assumed to be 380 kV

The study reported that distributed grid operators are faced with technical challenges such as voltage rises, reactive power control, and islanding from high penetration LV/MV levels. Again, both scenarios (first 25 GW installation in North Africa and second 50 GW among the EU Countries) require a revision and an upgrade of the transmission grid in order to avoid congestion. The study concluded that the second scenario ends up being less critical than the first one.

Additionally, a study on the impacts of large-scale photovoltaic power station on power grid voltage Profile, [12], used a simple but accurate method based on power system analysis principle to investigate the effects of large-scale photovoltaic energy integration on the transmission line. Three different power stations were selected for comparison with 100 MVA as base power and the rated voltage as the base voltage. Additionally, an inverter of 400 V was selected with the voltage level of HV transmission line being 110 kV. Two transformers were selected to prompt voltage level from 400 V to 10 kV and 10 kV to 110 kV respectively. The penetration scenarios were 200 kWp, 2 MWp and 10 MWp.

From the results the study concluded the bus voltage presents a parabolic trend with the PV power output increasing; there is a maximum voltage point on each Voltage-Power curve, with the corresponding PV power output determined by the impedances. The bus voltage sensitivity is also a nonlinear function of PV power output.

The anticipated effect of Solar Resource Variability on the Future Florida Transmission and Distribution System was reported in [13]. Using 11years historical weather data, the study developed a tool to simulate the photovoltaic energy system in several scenarios. A simulation model tool known as Solar Anywhere standard resolution was used to evaluate the high penetration of PV scenarios using an industry-standard of performance model.

For a good PV output variability examination, PV systems with different tilt and orientations were selected along with varying solar irradiance across Florida. Using three different penetration scenarios (a. 1.0 kW PV system in each 10x10 km grid 1800 orientation of true south, b. different, random direction facing generally south and between 900 east and 2700 west, c. the statewide grid was model with distributed generation roughly located with and proportional to population density) variability and high penetration PV were investigated.

The study reported that in all the scenarios, the variability was consistent, not only from hour to hour, but also between months. The results depicted an average hourly change in PV output as a changing percentage of the system's rated capacity. The study further concluded that variability was verified to be greater for smaller systems. Additionally, developing solar variability can quantify daily variability and ramp rates for different PV system layouts.

The influence of large-scale PV on voltage stability of sub-transmission systems has been reported in [14]. The study used the IEEE-14 bus test system to report the result of static voltage stability with large-scale PV penetrations on sub-transmission system for realistic load composition.. The performances of SVC and STATCOM were studied and compared to determine their impact on voltage stability.

The results of the study show that with constant power factor (0.95 leads-lags) and voltage control mode operations of PV, there are significant differences in the voltage value. Integration of PV to the system with constant power factor operation reduces the systems with constant stability from 2.6855 to 1.5706. However, the results show a significant difference when the same integration is operated in voltage control mode. With this mode, the degree of system stability rather improves from 2.6855 to 3.6155.

The paper also shows the effect of concentrated PV penetration on the degree of system stability. It was reported that for all the buses, increased PV penetration has a negative impact on system stability. The manner of PV integration (whether concentrated or dispersed), location and size all have a direct impact on system static voltage stability. It was also discovered during the study that voltage stability deteriorates with the integration of power factor operated PV, whereas in some instances voltage stability improves with the integration of voltage control mode operated PV.

Additionally, it was shown in that the placement of STATCOM based on short term-VAr helps to mitigate the low voltage ride through problem, and further provides higher system loading as compared to STATCOM placement at the weakest bus and at PV generator buses. STATCOM provides a better option for enhancing the static voltage stability margin of the system with large-scale PVs, and Placement of SVCs in PV generator buses is found to be more effective in enhancing voltage stability margin, rather than the weakest bus placement or placement based on short term dynamic VAr support.

When a significant amount of Solar PV is integrated into the grid, it alters the stability and operation of the power system. A study on the impact of Large Scale and High Voltage Level Photovoltaic Penetration on the Security and Stability of Power Systems, [15], discussed new requirements that might be brought to network simulation and calculation technology by grid-connected photovoltaic systems. The technical ramifications of the grid integration of large scale solar PV were reported to be effects on electricity quality, power flow control, new requirements for simulation technologies and power system test environment, voltage and frequency stability, codes and standards revising or supplementing of grid operation and dispatching.

Furthermore, the study suggested some research fields worth looking into to meet the practical and research requirements of solar PV integration. Among these were: 1) modeling methods of PV systems; 2) dynamic characteristics of power grid with PV systems connected; 3) power systems analyzing and calculating technology with PV systems contained;

4) control technology of grid-connected PV systems; and 5) revising and supplementing of the existing power systems rules and codes.

In one of the largest regional solar and wind integration and transmission studies conducted by NREL with GE [16], an attempt was made to investigate the operational impact of up to 35% energy penetration of wind, photovoltaic and concentrating solar power (CSP) on the power network operated by the WestConnect group.

With the use of a multidimensional scenario-based study approach, WWSIS evaluated different penetration levels (10% wind and 1% solar, 20% wind and 3% solar and 30% wind and 5% solar) for wind and solar power in different geographic locations. The project performance was evaluated through a combination of statistical analysis, hourly production simulation analysis, sub-hourly analysis using minute-to-minute simulations, and resource adequacy analysis.

One of the principal conclusions of the study was that forecasting solar or wind energy sources are critically essential for the reduction of short falls. Perfect forecasts will reduce the annual costs of renewable energy for the Western Electricity Coordinating Council by a projected $500million. With full utilization of existing transmission capacity, up to 20% of renewable energy penetration could be achieved with little or no new long distance, interstate and transmission additions. Finally, the study showed that it is operationally feasible to accommodate 30% wind and 5% solar energy penetration, on the condition that the some changes to current practice are made over time.

The Impacts on the Transmission Grid for Integrations of Renewable Energy in Taiwan was discussed in [17]. In addition to reviewing Taiwan's renewable energy policy and recent developments on the integration of renewable energy in the transmission grid, the paper reported the impacts of integrating renewable energy on the transmission grid. Limited transmission capacity has caused the Taiwan Government to approve Taipower's seventh transmission and substation plan from 2010 through 2015, which will add another 2,370ckt-km transmission line and total substation capacity of 23560 MWA to the grid by 2015, with SVC, STATCOM and SPS included, thus ensuring system stability and power quality.

A study conducted by California ISO (CAISO) assessed different types of solar PV generator interconnections [18].The study analyzed and reported several transient stability and voltage phenomena related to solar PV generator interconnections. The queue-base methodology, which requires generation developers to submit interconnected requests, was used in the research. It was reported that the interaction between the solar PV generators and the system amplifies the oscillation and causes unstable conditions. The research concluded that Solar PV generator interconnection may cause oscillation problems following faults, high voltage problems in sub-transmission and distribution systems under normal conditions, and the transient over-voltage problem in the grid following faults.

The study recommended that in order to maintain reliability with extensive interconnection of solar PV into the system, at both transmission and distribution levels, the accuracy of the solar PV generator modeling be verified, and the technology improved.

In all studies and cases thus considered, it is evident that the integration of large-scale solar PV into the transmission grid presents a unique set of technical challenges that demand to be addressed.

CHAPTERS THREE

3.0 RE DEVELOPMENT AND SOLAR PV INTEGRATION CHALLENGES

Globally, RE industries are in the midst of a tremendous change. All RE indicators project significant growth in development of this sector. Access to reliable energy supply, climate change and the high price of fossil fuel have all underpinned the need for the development and generation of renewable energy, [19][20]. The challenge of ensuring energy availability while preserving the environment has caused governmental action at the international, national and local levels to create a wide variety of laws and policies promoting RE development. This chapter will discuss the drivers of RE generation and development, present and future projects and technical challenges associated with integrating them into transmission grid.

3.1 Drivers of RE Development and Generation

Stabilizing climate impact from fossil fuel use, meeting the energy demand of a growing population, bringing electricity to people without access, ensuring stable and secure energy access for all nations and transporting electricity long distances from where it is generated to where it is used are some of the reasons for the unprecedented statistics of RE development and generation. RE is a growing component of electricity grids around the world due to its contributions to energy system decarbonization, long-term energy security, and expansion of energy access to new energy consumers in the developing world. [5][14]

3.1.1 Decarbonization

Climate change has been identified as one of the gravest threats to all nations, governments, businesses and the globe at large. The MSB EEE Report notes that CO2 emissions related to energy use account for 70 % of total GHG emissions, and those emissions related to electricity generation approach half of that. [21] Consequently, governments have enacted policies to curb GHG emissions from the power sector. Because electricity generated from RE produces no GHG emissions, increasing penetrations of RE onto the electrical grid contribute to a decarbonization of the electricity system: a reduction in GHGs emitted per unit of energy produced. Energy system decarbonization in turn slows the increase in concentrations of GHGs in the atmosphere and thereby mitigates the resultant radiactive forcing of the climate system [5]. Since the implications of climate change have a direct effect on both human and natural systems thereby leading to significant changes in resources and economic activities, it is plausible to seek to develop the renewable energy sector to mitigate GHG emission.

3.1.2 Energy Security

The world demand for energy is ever increasing and the growing concern of sustainable energy development has raised a red flag on the world's dependence of fossil fuels for a large percentage of electricity production. Because fossil fuel supplies are both unevenly distributed and ultimately exhaustible, many countries have identified a long-term energy security proposition in gradually decreasing dependence on them in the production of electricity. In comparison to fossil resources, renewable resources are better distributed throughout the world and do not diminish as they are used. A country's investment in RE results in a zero-fuel cost generation resource that is domestically located. Thus, even countries with substantial fossil fuel resources, such as China, have set aggressive wind power targets. And despite a recent boom in natural gas production in the USA, states have made no indication of any intent to remove RE goals. [5][22]

3.1.3 Expansion of Energy Access

The United Nations Millennium Development Goals, which aim to eradicate extreme poverty, can only be possible by providing reliable and affordable energy for all. In addition to the needs outlined in the previous subsections for cleaner and more secure energy, the world simply needs more energy as more people in the developing world gain access to it. As global energy demand increases, RE provides one means among many of adding energy assets to the system alongside growth of other resources. IEA's New Policies Scenario projects a near tripling of global use of RE, from 3 900 TWh in 2009 to 11 100 TWh in 2035, and growth in renewables accounts for nearly half of the total increase in generation by 2035. Indeed, under this scenario, a full third of global electricity generation will be supplied by RE (including hydroelectricity) by 2035. [5]

3.2 Renewable Energy Generation: Present and Future Projections

The use of renewable energy sources to generate electricity expands significantly in all three scenarios projected by the World Energy Outlook. In the New Policies Scenario, renewables-based electricity generation worldwide almost triples, from 3 900 TWh in 2009 to 11 100 TWh in 2035. This expansion is primarily driven by government policies, including subsidies, and represents 44% of the growth in total electricity generation through the course of the Outlook

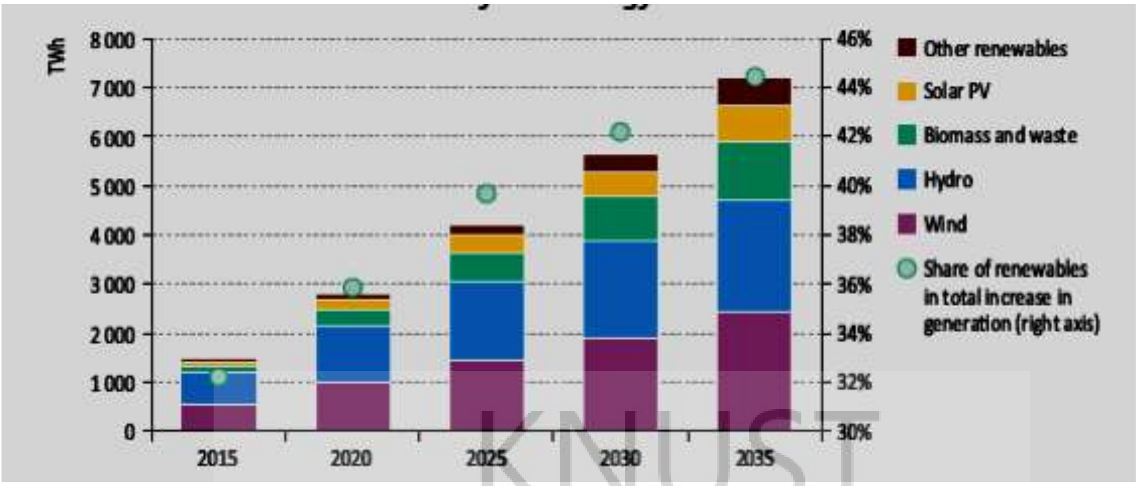


Figure 2.1, Incremental global renewables-based electricity generation relative to 2009 by technology in the New Policies Scenario International Energy Agency [2]

3.2.1 Solar

The growth trend of Solar Photovoltaic (PV) electricity generation in 2011 was very remarkable. The grid integration for 2011 was 29.7 GW as compare to 16.8 GW in 2010 making it the third most important renewable energy source in terms of global installation capacity. Europe dominated with about 75% of new capacity in 2011 with Italy topping the market with 9.3 GW connected followed by Germany with 7.5 GW. [23]

Solar PV electricity generation increases substantially over the Outlook period, from 20 TWh in 2009 to 740 TWh in 2035 in the New Policies Scenario, growing at an average rate of 15% per year. The European Union accounted for three-quarters of global solar PV generation in 2010. This has been driven by strong government programmes, particularly in Germany where there has been rapid growth in recent years. Over the early years of the Outlook period, Europe continues to exhibit very strong growth in solar PV but, between 2020 and 2035, the increase in solar PV generation in each of China, the United States and India is larger than that in the European Union. [2]

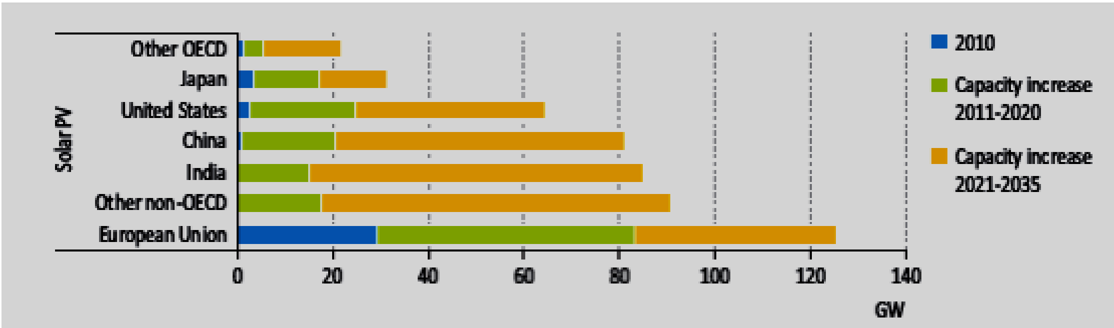


Figure 2.2, Solar PV and wind power capacity by region in the New Policies Scenario by International Energy Agency

3.3 SOLAR PV INTEGRATION CHALLENGES

On the normal system level, RE power plants generate electricity like any other power plants. But RE has unique characteristics in generation, transmission and operational technology. Understanding these distinctive characteristics is the basis for the integration of large-capacity RE power in the grid. [5] The following are some of the challenges that can exist when integrating large share Renewable Energy into current electrical power systems:

3.3.1 Voltage Rise

Voltage rise is caused by high penetration of solar PV into the utility grid. It is when there is an increase in voltage at the inverter side relative to the utility voltage When solar PV is connected to the grid via the inverter, the impedance from the grid and inverter output-circuit conductors causes the rise in voltage which is negative voltage drop on the circuit between the inverter and the point of common coupling (PCC). [24]

Current Utility grids do not anticipate this condition and can cause overvoltage tripping at the inverter and this will affect the overall performance of the grid. Neutral voltage rise can also occur when there is an imbalance of loads and high PV generation on three phase power system hence determination of an acceptance penetration level that a power system can accommodate is inevitable in solar PV integration. Voltage rise is controlled by a power conditioner for PV systems designed and used in Japan, to ensure that the limit is not exceeded. This technology can prevent over-voltage but the PV system efficiency is affected because the PV power output is dumped to control the voltage. [25]

3.3.2 Voltage Stability

Voltage stability is defined as a phenomenon where a power system maintains steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. Voltage stability depends on the ability to maintain or restore equilibrium between load demand and load supply of a power system. When the need for reactive power in a power network system is met, voltage stability can be achieved. [26]

Inverters are responsible for keeping the power factor of the PV system at unity. When the power factor is at unity there is no exchange of reactive power between the inverter and the grid. This becomes problematic when solar PV is connected to a weak grid and the capacity is large, static voltage instability problems will occur since the PV system will draw reactive power [27]

3.3.3 Harmonics

Current produced by a solar PV system is a direct current. The inverter interface between the Solar PV and the grid works by converting DC current to AC current through a semiconductor switching circuit, but the AC wave obtained from the devices will not be a perfect sinusoidal wave. The introduce harmonics into the power network. In countries like Australia and Greece, the total harmonic distortion should not exceed 5%. This figure is different in Germany, which gives a harmonic distortion allowance of up to 8% for inverter current up to the 50th harmonic. [28][29]

3.3.4 Islanding

Unintended islanding is an electrical phenomenon where an on-grid solar PV system continues to supply power to the grid even when the utility side is disconnected. This energizes the utility feeders, posing a danger to personnel working on the feeders. [30]

3.3.5 Power Quality

Solar PV generation output depends hugely on temperature and irradiance. Change in climate conditions such us cloud cover may cause voltage flickers. In the case of high penetration level of the PV systems, the impact is higher and it can affect the quality of power supply to the grid. [31]

3.3.6 Technical Expertise:

Development of large-scale renewable energy resources requires skilled labor and capacity building to implement, operate and maintain. According to International Renewable Energy Agency [32], there are a limited number of skilled personnel working in the renewable energy sector worldwide. Installation or construction of plants and operation, as well as the maintenance and decommissioning of RE plants require a number of skilled engineers and technicians. Without these personnel and a clear understanding of renewable energy grid integration, sector development, especially in Africa, has been stunted. [33]

3.3.7 Location Dependency

The best wind and solar resources are location dependent and cannot be transported to optimal sites like coal, oil or gas. Therefore, renewable energy generated needs to be transported over considerable distances to load centers where the power will ultimately be used. In most situations, additional transmission infrastructures are required to connect RE resources into the rest of the grid and this increases connection costs and thereby reduces the competitiveness of these projects. [5]

This challenge is very evident in China where their windy regions are often far from the population and load centers. There is also a wide distance between Scotland's tidal current resources and where significant of the population live. Midwest regions of US have high quality of wind resources while many Americans live in coastal regions. [34]

3.3.8 Non-controllable variability

Solar and wind output varies in many ways that make it extremely difficult for generation operators to control. This is because the speed of the wind and available sunlight varies moment by moment, thus affecting moment by moment power output. The fluctuation makes it more difficult and challenging to strike the balance between supply and demand on the grid in more ways than one. This fluctuation affects ancillary services such as frequency and voltage. [5]Frequency and demand response stands as one of the biggest challenge of renewable energy large-scale grid integration.

3.3.9 Partial unpredictability

Wind turbines depend largely on the blowing wind for electricity production and solar PV systems need sunlight for operation, but the wind and sunlight availability is partially unpredictable. [5] Consequently, solar PV electricity generation companies are at the mercy of the inherent unpredictability of sunlight.

CHAPTER FOUR

4.0 SOLAR PV SYSTEMS AND GRID INTEGRATION

This chapter will give a general overview of generation, transmission and distribution segments in Ghana. It will outline progressive development of Renewable energy in Ghana. Lastly the theory of solar PV grid-connected system integration and electrical characteristics of solar PV will be discussed.

4.1 OVERVIEW OF POWER GENERATION, TRANSMISSION AND DISTRIBUTION SEGMENTS IN GHANA

Electricity is the dominant modern form of energy used in the industrial and service sectors, accounting for 69% of modern energy used in the two sectors of the national economy. The generation and supply of electricity provides employment for a significant number of Ghanaian professionals. It is also an important source of foreign exchange earnings in the country as Ghana exports power to neighboring countries, including Togo, Benin, and Burkina Faso. The Ghana electricity supply industry is unbundled with separate jurisdictions and entities regarding activities of electricity generation, transmission and distribution. [35]

4.1.1 Generations

Volta River Authority is a state-owned company mandated to generate electricity to meet the domestic demand of Ghana and export opportunities. It operates the Akosombo Hydro Power Station, Kpong Hydro Power Station and the Takoradi Thermal Power Plant at Aboadze. VRA is also a minority joint partner with TAQA, a private sector company which owns and operates the Takoradi International Power Company thermal power plant also located at Aboadze.

Bui Power Authority (BPA), another state-owned entity, is charged with the implementation of the Bui Hydroelectric Power Project. In addition, Independent Power Producers have been licensed to build, own and operate power plants. The IPP projects are at various stages of development. [35]

4.1.2 Transmission

GRIDCo was established in accordance with the Energy Commission Act, 1997 (Act 51) and Volta River Development (Amendment) Act, 2005 Act 692, which provides for the establishment and exclusive operation of the National Interconnected Transmission Systems by an independent utility and separation from the transmission function of the VRA from its other activities within the framework of the power sector reform.

GRIDCo is mandated to undertake the economic dispatch and transmission of electricity from the whole supplier (generating companies) to the bulk customers (distributing companies). GRIDCo was commissioned to carry out transmission systems planning and also provide fair and non-discriminatory transmission services to all power market participants. [36]

Table 4.1 Summary of Ghana National Transmission Grid facts [36]

Fact Sheet on Transmission Network - Transmission Line Length - 4,315.5 km	
330 kV	219.5 km
161 kV	3888.1 km
225 kV	73.4 km
69 kV	132.8 km
No of Transformers(Including spares)	100
Transformer Capacity	2915 MW
No of Transformer and Switching Substations	53
Largest switching Substations is Volta Substation	Tema
Transformer Substations	330/161 kV, 161/69 kV, 161/34.5 kV, 161/11.5 kV

4.1.3 Distribution

The distribution of electricity in Ghana is dominated by two companies, the state-owned Electricity Company of Ghana, and the Northern Electricity Distribution Company (NEDCo), a subsidiary of VRA.

4.1.3.1 Electricity Company of Ghana

Electricity Company of Ghana is a limited liability company wholly owned by the Government of Ghana and operating under the Ministry of Energy. The company was incorporated under the Companies Code, 1963 in February 1997. It began as the Electricity Department on 1st April 1947 and later became the Electricity Division in 1962. It was subsequently converted into the Electricity Corporation of Ghana by NLC Decree 125 in 1967 [37]

The company is charged with the responsibilities to transmit, supply and distribute electricity all its customers in the southern part of Ghana (Ashanti, Central, Greater Accra, Eastern and Volta Regions of Ghana). The company purchases electricity energy in bulk (from the Volta River Authority) or any other supplier for distribution. They also construct, reconstruct, install, assemble, repair, maintain, operate or remove sub-transmission stations, electrical appliances, fittings and installations to enhance an effective supply of electricity to customers. [37]

4.1.3.2 Northern Electricity Distribution Company

This subsidiary of VRA is given a similar mandate as ECG to transmit, supply and distribute electricity all its customers in the Northern part of Ghana (Brong-Ahafo, Northern, Upper East and Upper West Regions).

4.2 RENEWABLE ENERGY POTENTIAL AND DEVELOPMENT IN GHANA

Under the National Energy Policy, the vision for the energy sector is to develop an "Energy Economy" that would ensure secure and reliable supply of high quality energy services for all (both urban and rural) Ghanaian homes, businesses, industries and the transport sector while making significant contribution to the export earnings of the country. [35]

The policy objective for the power sector is to increase installed generation capacity from 1986MW to 5000MW by 2020. The overall national renewable energy policy target is to attain 10% (500MW) Renewable Energy (excluding large hydro) in the national energy mix by 2020.

4.2.1 Renewable Energy Directorate

With government's commitment to the development of the renewable energy sector, the Renewable Energy Unit at the Ministry of Energy has been upgraded to a full Directorate similar to the Petroleum and Power Directorates. This Directorate was established in December 2010 to focus on the development and promotion of renewable energy for increasing access to sustainable energy services.

4.2.2 Renewable Energy Law (Act 832)

The Renewable Energy Bill was passed by Parliament, has received Presidential assent, and has since been gazetted - The Renewable Energy Act 2011 (Act 832). The Act is aimed at providing the fiscal incentives and the regulatory framework to encourage private sector investment into the sector. Among the key provisions in the act are:

- Feed-in-Tariff Scheme, under which electricity generated from renewable energy sources will be offered a guarantee price.
- Renewable Energy Purchase Obligations, under which power distribution utilities and bulk electricity consumers will be obliged to purchase certain percentage of their energy requirement from electricity generated from renewable energy sources.
- Licensing regime for Commercial Renewable Energy Service Providers, among others, to ensure transparency of operations in the renewable energy industry.
- The establishment of the Renewable Energy Fund to provide incentives for the promotion, development and utilization of renewable energy resources.

4.2.3 Solar Potential in Ghana

Ghana is endowed with enormous solar energy resource spread across the entire country. Daily solar irradiation level ranges from 4 kWh/m2 to 6 kWh/m2. Areas of highest irradiation levels are spread across the entire northern belt which represents over 60% of the total national land mass. The annual sunshine duration ranges between 1800 to 3000 hours offering very high potential for grid connected and off-grid applications. Over 6,000 solar systems with an installed capacity of 3.2 MW have been installed in the country mainly for off-grid applications. [38]

4.3 PHOTOVOLTAIC POWER GENERATION AND CHARACTERISTICS

4.3.1 Solar Cell

A solar cell is an electrical device that converts the energy of light into Direct Current (DC) electricity. Groups of PV cells can be used to charge batteries, operate motors and to power any number of electrical loads. With right power conversion equipment, PV systems can produce alternating current (AC) compatible with any conventional appliances, and can operate in parallel with, and interconnected to, the utility grid. A solar cell is in a form of photoelectric cells whose electrical characteristics vary when it is exposed to light and can generate and support an electric current without any external voltage source. [39]

4.3.2 How Solar PV Cells Works

A photovoltaic cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorus doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. At the p-n junction near the top surface of the cell an electrical field is created. When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load. A typical silicon PV cell produces about 0.5 - 0.6 volt DC under open-circuit, no-load conditions. The current (and power) output of a PV cell depends on its efficiency and size (surface area), and is proportional to the intensity of sunlight striking the surface of the cell. The internally generated photocurrent in a solar cell is proportional to the irradiance. [40][41]

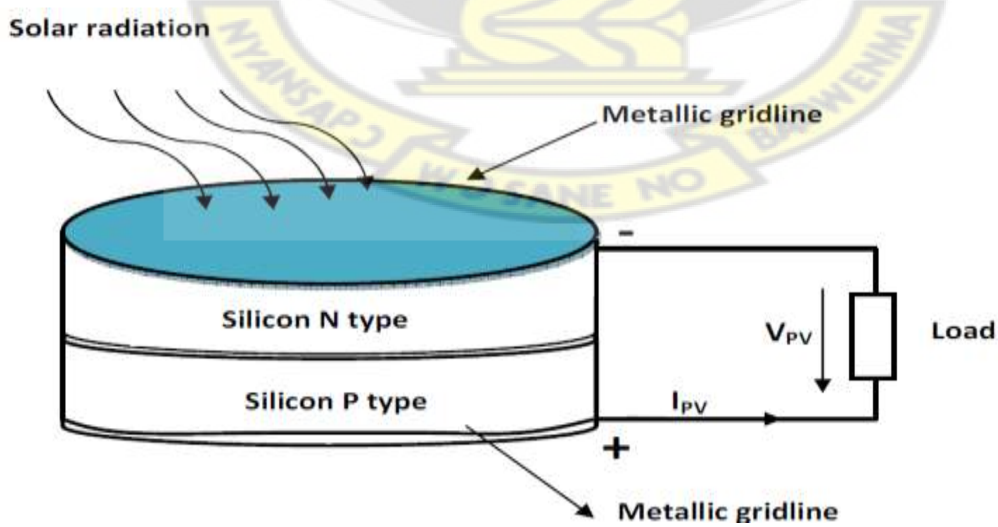


Figure 4.1: Elementary photocell structure, [41]

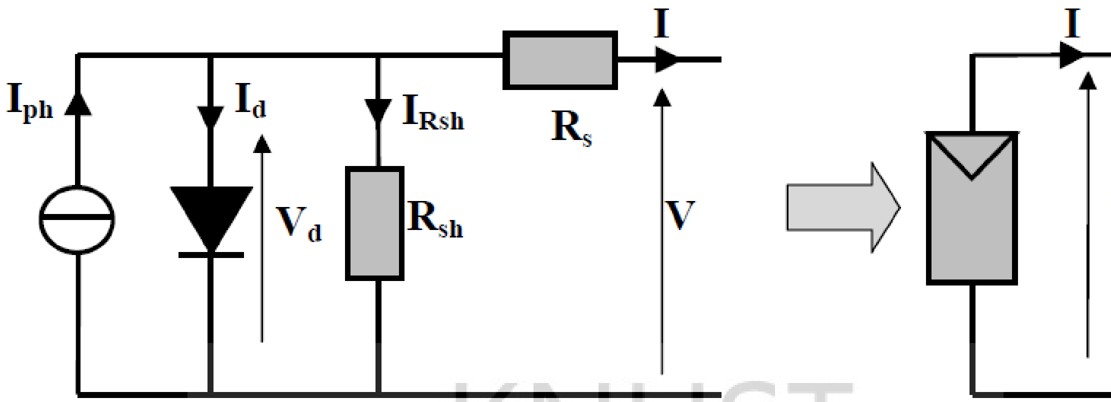


Figure 4.2 Electrical model of real photocell [41]

$$I = I_{ph} - I_d - I_{R_{sh}} \qquad (1)$$

Where:

$$I_{ph} = I_{sc}\left(\frac{\Phi}{1000}\right) \qquad (2)$$

$$I_d = I_o\left[\frac{q\,(V + r_s I)}{e^{nkT} - 1}\right] \qquad (3)$$

$$I_{R_{sh}} = \frac{V + r_s I}{R_{sh}} \qquad (4)$$

Considering the equivalents of I_{ph}, I_d and $I_{R_{sh}}$ the mathematical model of the real photocell is the following:

$$I = I_{sc}\left(\frac{\Phi}{1000}\right) - I_o\left(\frac{q(V + r_s I)}{e^{V_t} - 1}\right) - \frac{V + r_s I}{r_{sh}} \qquad (5)$$

Where:

$$V_T = \frac{nkT}{q} \qquad (6)$$

I_{ph} = Photocurrent

I_d = Diode’s current

$\boldsymbol{I_{R_{sh}}} =$ Current diverted by the shunt resistance Rsh

$\boldsymbol{I_o} =$ Dark current (Reverse saturation current of the diode),

$\boldsymbol{q} =$ charge of electron, 1.60 x 10^{-19}C

$\kappa =$ Boltzmann's constant, 1.38 x 10^{-23}J/K

$V =$ Voltage output (V)

$I_{sc} =$ Short circuit current (A)

$\boldsymbol{\Phi} =$ Irradiation (W/m^2)

4.3.3 Standard Test Conditions

Standard test conditions (STC) for terrestrial solar power modules is used to compare the performance of different solar power modules uniform operating data. These conditions define performance at incident sunlight of 1000 W/m², a cell temperature of 25°C (77°F) and an Air Mass of 1.5. [42]

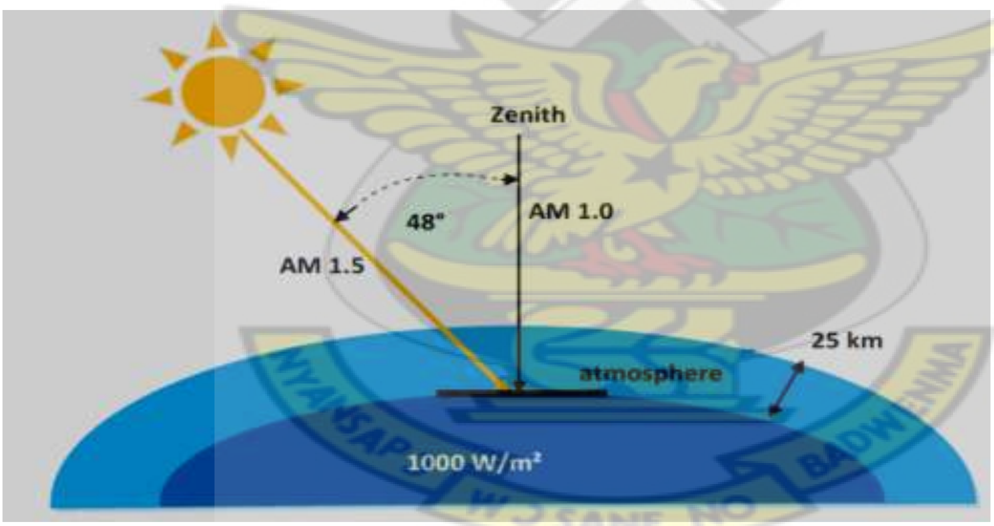


Figure 4.3: Air mass [41]

4.3.4 Solar Irradiance and Temperature Effects

Solar irradiance and temperature have a direct effect of the characteristics of solar PV and hence its generation and efficiency. Solar irradiation is the measure incident of total amount of solar radiation transmitted to the surface of the Earth's atmosphere in a given unit of time. It is time integral of the irradiance extended over a given period of time, therefore radiation units are units of energy (J/m²/day, kWh/m²/day or kWh/m²/month. [43]

The MPP varies during the day and that is the main reason why the MPP must constantly be tracked and ensure that the maximum available power is obtained from the panel. The effect of the irradiance on the voltage-current (V-I) and voltage-power (V-P) characteristics is depicted in Figure 4.4, where the curves are shown in per unit, i.e. the voltage and current are normalized using the Voc and the Isc respectively, in order to illustrate better the effects of the irradiance on the V-I and V-P curves [44].

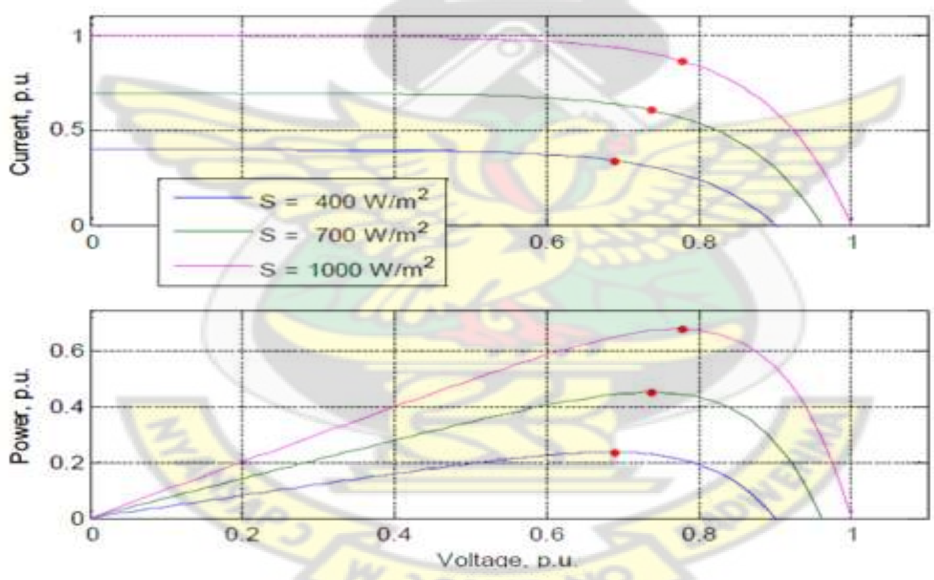


Figure 4.4: V-I and V-P curves at constant temperature (250C) and three different insolation values

The open circuit voltage is linearly dependent on the temperature, as shown in the equation below:

$$V_\alpha(T) = V_\alpha^{STC} + \frac{K_{v,\%}}{100}\,(T - 273.15)$$

The effect of the temperature on Voc is negative, because Kv,% is negative, i.e., when the temperature rises, the voltage decreases. The current increases with the temperature but very little and it does not compensate the decrease in the voltage caused by a given temperature rise.

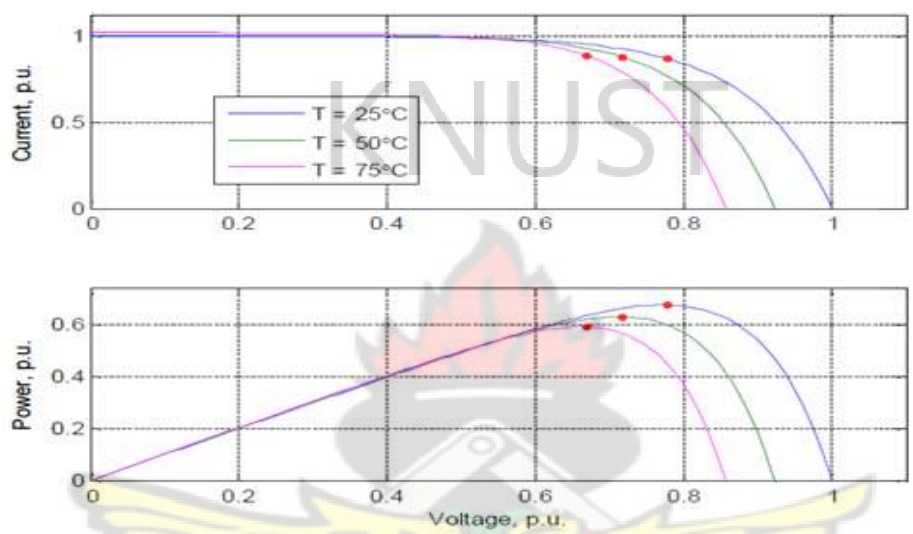


Figure 4.5: V-I and V-P curves at constant irradiation (1 KW/m2) and three different temperatures

4.3.4 Peak Sun Hour

The number of peak sun hours for the day is the number of hours for which energy at the rate of1kW/m² would give an equivalent amount of energy to the total energy for that day. It is equivalent number of hours per day when solar irradiance averages 1000 w/m2. [45][41]

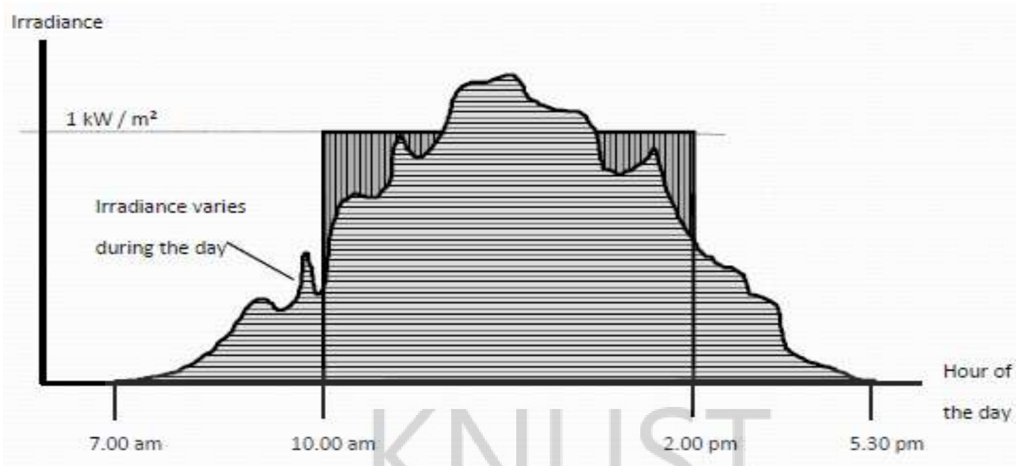


Figure 4.4: Typical variation of Solar Irradiance [41]

4.3.5 Characteristic Voltage-Current I (V)

The standard representation of the output of a PV device is called the current-voltage curve. I-V measurement determine the output performance of solar PV, including: open-circuit voltage (Voc), short-circuit current (Isc), voltage at maximum power (Vmax), current at and current maximum power (Imax). The letter "I" is usually used to represent electrical current and the “V” operating voltage range. At high voltage, the relatively level current rapidly falls off past a "knee" region on the curve.

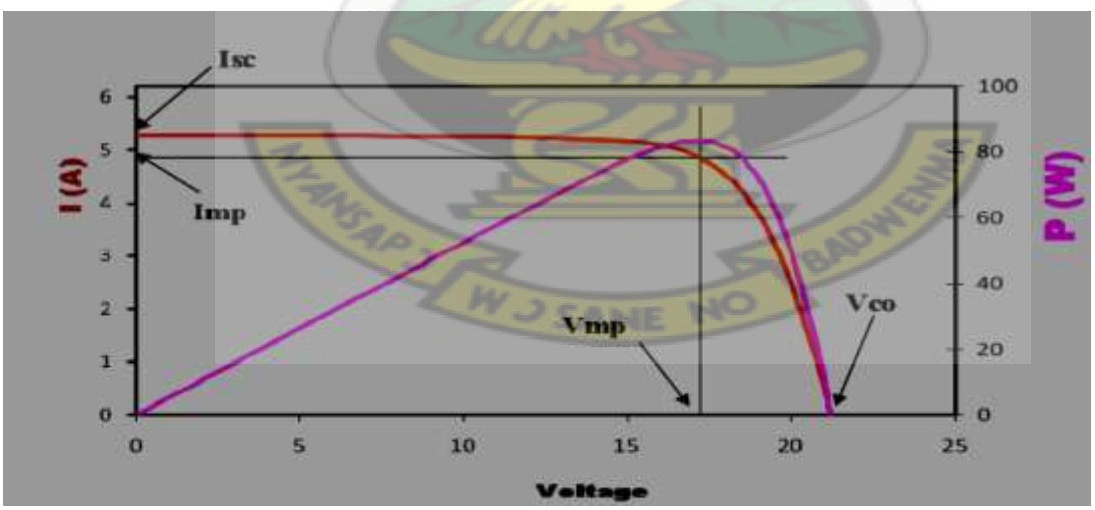


Figure 4.5 Characteristic I (V) of a module MSX-83 from BP Solar and power curve at STC [41]

$I_{sc} = Short\ Cuiruit\ Current$

$V_{oc} = Open\ Circuit\ Voltage$

$I_{mp} = Current\ that\ results\ in\ Maximum\ power\ under\ given\ condition$

$V_{mp} = Voltage\ that\ results\ in\ Maximum\ power\ under\ given\ condition$

$P_{max} = Maximum\ output\ power\ under\ given\ condition$

4.3.6 Peak Power (kWp) of the Array at STC

This value specifies the output power achieved by a solar module under set Standard Test Conditions. Peak power is also referred to as "nominal power" by most manufacturers since it is based on measurements under optimum conditions. The peak power is different from the power under actual radiation conditions and practically it will be approximately 15-20% lower due to the considerable heating of the solar cells. [39]

$$P_o = G_o\ x\ A\ x\ \eta_m \qquad (kWp) \qquad (7)$$

P_o = peak power

$G_o = 1000\ w/m^2$

A = Available area

η_m = efficiency

Number of Modules for a PV generator

$$P_{o(Array)} = P_{mmp}\ x\ N_m) \qquad (8)$$

$P_{o(Array)}$ = peak power of the array

P_{mmp} = Normal power

N_m = number of modules

4.4 PHOTOVOLTAIC SYSTEMS

Classification of Photovoltaic systems can be done based on their functional and operational requirements, their component configurations and how the system is connected to either power sources or electrical loads. Based on system connectivity, we have standalone and grid-connected system. Since the focus of the thesis is grid connected, we will explore the various connection and components of grid connected.

4.4.1 Grid Connected Solar PV Systems

Grid-connected, also known as utility-interactive PV systems are designed to operate with and interconnected to electrical utility grid. In grid-connected systems, the inverter is the primary component. The inverter converts the DC power produced the PV array into AC power consistent with the voltage and power quality requirements of the utility grid. The inverter stops the PV array from supplying power when the utility is not energized. This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or maintenance. [47]

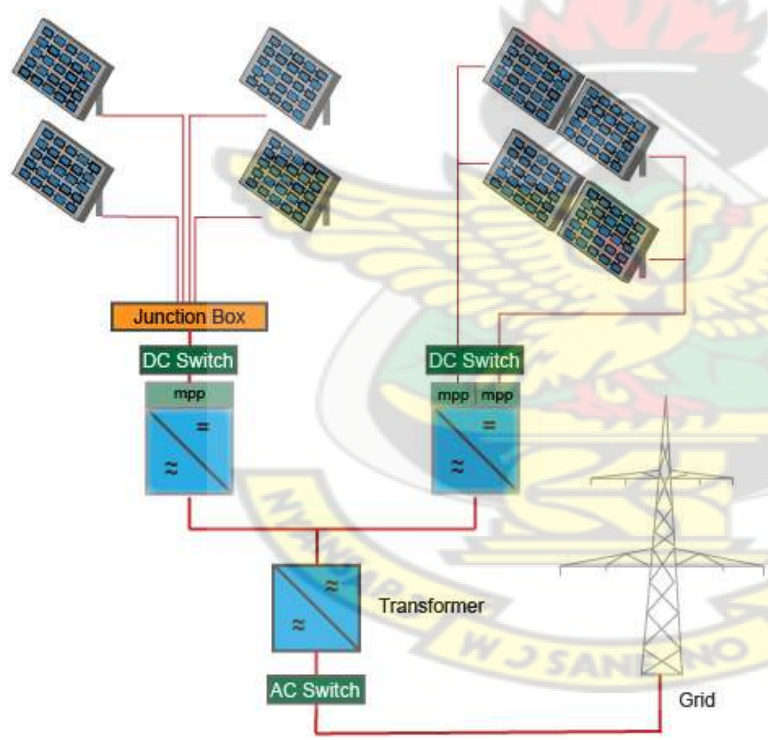


Figure 4.6: Grid-Connected system [47]

4.4.1.1 Junction Box

Multiple modules are connected through a junction box, to provide surge protection. [47]

4.4.1.2 DC Switch

Solar generators must be separated from the inverter in order to undertake repairs or general maintenance work on the systems. This is achieved by a DC switch installed closer to the inverter. DC switch copes with the short-circuit current as well as the open-circuit voltage as the modules continue to generate electricity. Some inverter manufacturers' offer integrated DC switches. [47]

4.4.1.3 Inverter

In commercial capacity category, 3 phase inverters are the most suitable choice for the PV systems. The DC power coming from the photovoltaic generator is converted into a utility frequency alternating current AC by the inverter before feeding it into the electric grid. Solar inverters have some special features maximum power point tracking and anti-islanding protection. The Solar PV inverters utilize a Maximum Power Point Tracking (MPPT) to find the maximum power through adjusting the voltage and current supplied from the PV panel. They can be categorized into three different types, namely standalone, grid-tier and battery backup inverters. [48]

4.4.1.3.1 Stand-Alone Inverter

The stand-alone inverters are especially used in isolated systems where the inverter draws DC energy from batteries that have been charged by the Solar PV panel. The inverters are designed to be used off grid. They can be run from Solar PV panels and batteries using a charge controller. The charge controller regulates the input from the Solar PV system and protects the batteries. It also regulates the battery output and controls the charging of the batteries. [48]

4.4.1.3.2 Grid Tier Inverter

The Grid-Tier inverters contain some special circuitry to precisely match the voltage and frequency of the electrical grid network. They are designed to be connected to the National Grid, and are designed to detect the presence of the National Grid and shut down automatically on occasions when supply is lost. Grid-tier inverters do not provide backup electricity during power cuts. [48]

4.4.1.3.3 Battery Backup Inverter

Battery back-up inverters are designed to draw energy from a battery, manage a battery charge via an on-board charger, and export excess energy to the electric grid. The Battery Backup Inverters are capable of supplying AC energy to selected loads during a power cut, and are required to have anti-islanding protection. [48]

4.4.1.4 Transformer

An optional transformer may step up the voltage to very high voltage required by the grid. [47]

4.4.1.5 AC Switch

An AC switch is required by grid operators to ensure safety. It automatically switches off the grid connection if current errors, changes in frequency or voltage are detected. [47]

4.5 SOLAR PV INTEGRATION CODES AND STANDARDS

Solar PV integration or interconnection can be done on different voltage levels. The recommendations from the California Independent System Operator Corporation (CAISO) suggest that due to their higher capacity, large-scale solar PV generators should be interconnected at the transmission level. Small-scale solar PV generators, however, mostly need to interconnect to the closest distribution or sub-transmission system. In [49] the interim status in identifying and reviewing photovoltaic PV codes and standards (C&S) was presented. Related electrical activities for grid-connected, high-penetration PV systems with utility distribution grid interconnection were also reported. Of note, not all identifying topics and concerns are in the existing C&S documents, thus there are some research projects ongoing, which would make recommendations for related C&S needs.

In their Special Report entitled "Accommodating High Levels of Variable Generation," the North American Electric Reliability Cooperation presented an inseparable link between design standards and requirements related to overall reliable performance of the bulk power system. It was outlined that there is a considerable work required by both generator owners and operators to standardize the basic requirements in interconnection procedures and standards. [50]

The effective and reliable interconnection and operation of renewable energy sources requires voltage regulation and reactive power capability; low and high voltage ride-through; inertial response (effective inertia as seen from the grid); control of the MW ramp rates and/or curtail MW output; and frequency control (governor action).

4.5.1 IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems

The IEEE Standard for interconnecting Distributed resources provides interconnection technical specifications and requirements, and test specifications and requirements. It provides interconnecting requirements relevant to the operation, testing, performance, safety considerations, and maintenance of the interconnection. The limitation of the interconnecting standards it is applicable to all distribution generation with aggregate capacity of 10 MWA or less at the point of common coupling, interconnected to EPSs at typical primary and/or secondary distribution voltages. The standard written on the assumption at the Distribution Resource is at 60 HZ source. Tables below are IEEE interconnection system response to abnormal voltages, abnormal frequency and maximum harmonic current distortion [51]

Table 4.2 Interconnection system response to abnormal voltages [51]

Voltage Range (% of base voltage)	**Clearing Time (s)**
$V < 50$	0.16
$50 \leq V < 88$	2.00
$110 < V < 120$	1.00
$V \geq 120$	0.16

Base voltages are the nominal system voltages stated in ANSI C84.1-1995, Table 1.

Clearing time(s): DR ≤ 30 kW, maximum clearing times; DR > 30kW, default clearing times Maintain service voltage within ANSI C84 Range A (+/-5%)

Table 4.3 Interconnection system response to abnormal frequencies [51]

DR Size	Frequency range (Hz)	Clearing Time (s)
≤ 30 kW	> 60.5	**0.16**
	< 59.3	**0.16**
≥ 30 kW	> 60.5	**0.16**
	< {59.8 - 57.0} (adjustable set point)	Adjustable 0.16 to 300
	< 57.0	**0.16**

DR ≤ 30 kW, maximum clearing times; DR > 30 kW, default clearing times

In Europe the standard61400-21 recommends to apply the standard61000-3-6 valid for polluting loads requiring the current THD smaller than 6-8 % depending on the type of network.

Table 4.4 Maximum harmonic current distortion in percent of current

harmonic	limit
5th	5-6 %
7th	3-4 %
11th	1.5-3 %
13th	1-2.5 %

4.6 GRID-INTERCONNECTION ISSUES WITH SOLAR PV

The following are electrical issues associated with grid-interconnections:

4.6.1 Voltage Fluctuation

Voltage fluctuation occurs when there is a swing in voltage, and this can have a negative impact on the system if it moves outside specified values. The swing in voltage can be high (overvoltage, which decreases the life span or damage equipment especially the electronic components) and low (undervoltage, which can affect the operation of some equipment) [52]

To help contribute to power quality and unintentional islanding, Inverters are generally configured to operate in grid 'voltage-following' mode and to disconnect when the grid voltage moves outside set parameters. In high penetration solar PV system, automatic disconnection due to the grid voltage being out of range can be problematic because other generators on the network will suddenly have to provide additional power. [52]

To solve this problem, voltage sag tolerances could be broadened and where possible, Low Voltage Ride-through Techniques (LVRT) could be incorporated into inverter design. LVRT allows inverters to continue to operate for a defined period if the grid voltage is moderately low but they will still disconnect rapidly if the grid voltage drops below a set level. In Germany, LVRT standards are now incorporated into grid-connection standards. [52]

4.6.2 Voltage imbalance

Voltage imbalance occurs when the amplitude of each phase voltage is different in a three-phase system. Single-phase systems installed disproportionately on a single phase can cause unbalanced networks leading to damage to controls, transformers, motors and power electronic devices. Hence, at high PV penetrations, the cumulative size of all systems connected to each phase should be as equal as possible. [52]

4.6.3 Voltage rise and reverse power flow

In a traditional centralized power networks, power flow in one direction only: from power plant to transmission network, to distribution network, to load. In order to accommodate line losses, voltage is usually supplied at 5-10% higher than the nominal end use voltage. Voltage regulators are also used to compensate for voltage drop and maintain the voltage in the designated range along the line. [52]

Recently, both the mix of centralized and distributed generators as well as the load determines power flows and voltages in the network. With high penetration so solar PV on feeders, localized overvoltage can occur, and the voltage at the load end may be greater than the voltage on the normal supply side of the line – this is known as the voltage rise and can result in reverse power flow. [52]

The four most common approaches currently used to minimize voltage rise and reverse power flow are applied to the PV systems themselves and involve (i) ensuring PV systems are smaller than the daytime load, (ii) use of a minimum import relay (MIR) to disconnect the PV system, (iii) use of a dynamically controlled inverter (DCI) to gradually reduce PV output, and (iv) use of a reverse power relay (RPR) to disconnect the PV system if the load drops to zero or reverses direction. [52]

4.6.4 Power factor correction

Power factor affects the quality of the power. Poor power factor on the grid increases line losses and makes voltage regulation more difficult to handle. Inverters configured to be "voltage-following" have unity power factor, while inverters in voltage-regulating mode provide current that is out of phase with the grid voltage and so provide power factor correction. This can be either a simple fixed power factor or one that is automatically controlled by, for example, the power system voltage. [52]

4.6.5 Frequency variation and regulation

Frequency is one of the most important factors in power quality and must be uniform throughout an interconnected grid. Disruptions in the balance between supply and demand lead to frequency fluctuation. Frequency regulation is generally maintained by control loops built into the power generating sources on the network. Because solar PV is intermittent nature, it makes frequency control more difficult. [52]

Inverters may of course be able to help with frequency control, and can provide frequency control in milliseconds, which is significantly faster than conventional generation. However, special control algorithms would need to be developed to take. [52]

4.6.6 Harmonics

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. Current produced by a solar PV system is a direct current. The inverter interface between the Solar PV and the grid works by converting DC current to AC current through a semiconductor switching circuit, but the AC wave obtained from the devices will not be a perfect sinusoidal wave. The introduce harmonics into the power network. In countries like Australia and Greece, the total harmonic distortion should not exceed 5%. This figure is different in Germany, which gives a harmonic distortion allowance of up to 8 % for inverter current up to the 50th harmonic. [28][29]

CHAPTER FIVE

5.0 METHODOLOGY AND IMPLEMENTATION (MODELING AND SIMULATION)

The chapter will discuss the modeling and simulation of the 2.0 MWp VRA project at Navrongo. Since the case study is real, modeling of the system would be done according to component purchased and data provided by VRA. Open Distribution System Simulator (Open-DSS) software will be used for the modeling and simulation in this chapter.

5.1 THE 2.0 MWP PV OF THE VRA'S RE DEVELOPMENT

The Volta River Authority has planned to increased their generation capacity by generation 2.0MWp Solar PV into the transmission grid. This is the first step of the company's vision to generate 10MW RE mix.

5.2 PROJECT SITE AND RESOURCES

Navrongo, a district in upper East part of Ghana, was selected for the first phase of the project. The feasibility study shows Navrongo as one of the best sites for this project because of its average yearly solar irradiance levels. Navrongo is located at 10°53′5″N 1°5′25″W.

5.1 Navrongo, 2.0 MWp Solar PV Project Site

5.2.1 Solar Irradiance and Air Temperature of Nanvrogo

Navrongo daily solar radiation is one of the reasons why the VRA selected it as a site for this project. Daily solar irradiation levels range from 4.90 kWh/m2 to 6.61 kWh/m2, with August and January recording worst and best month respectively. The average daily solar radiation for the year is 6.10 kWh/m2. The temperature also ranges from 24.1 ^{0}C to 29.90 ^{0}C, with 27.1 ^{0}C been the annual average. [53]

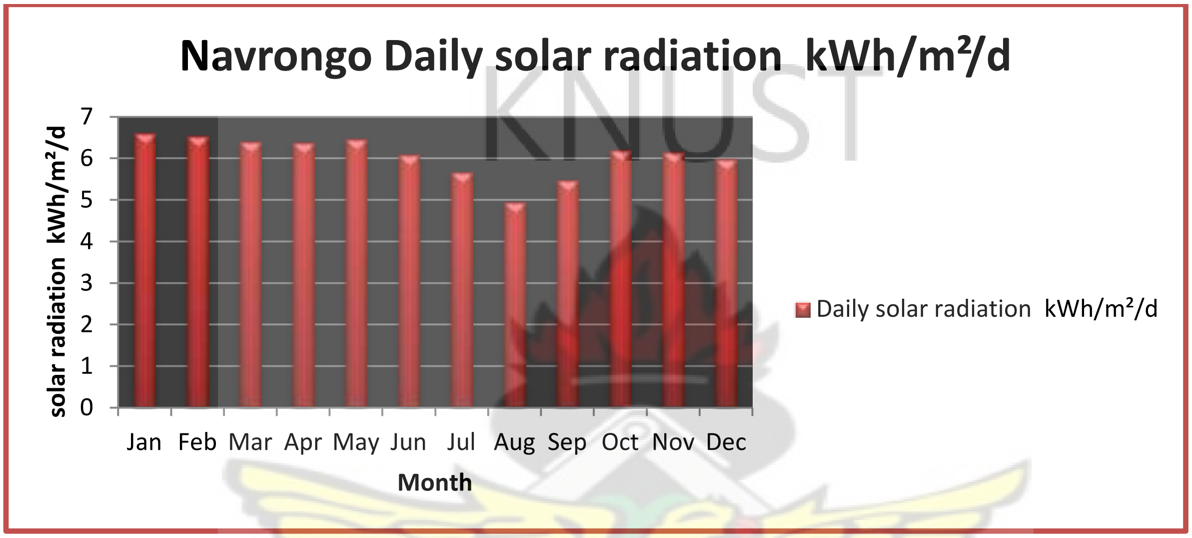


Figure 5.2: Navrongo Daily Solar Radiation (kWh/m²/d), RETScreen

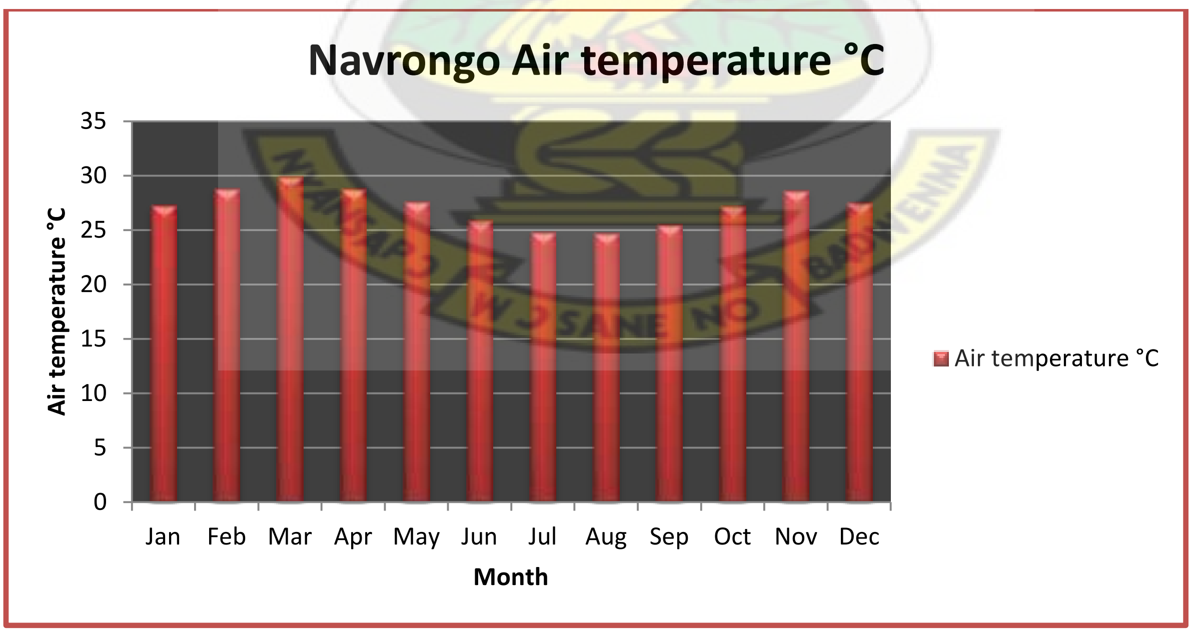


Figure 5.3: Navrongo Daily Air temperature °C, RETScreen

5.2.2 Single Line Diagram and Load Details of Navrongo Network

The diagram in figure 5.4 shows the single line diagram of the Navrongo power network. The distance between the take off bus and the Navrongo 34.5 kV bus is 27.4 km. The Navrongo 34.5 kV bus serves Tumu and Sadema. Much of the load is concentrated on the Navrongo 34.5 kV bus and that is where the Solar PV is injected into the grid. The total apparent load on the network is 3762.34 kVA with the active load been 3.502 MW.

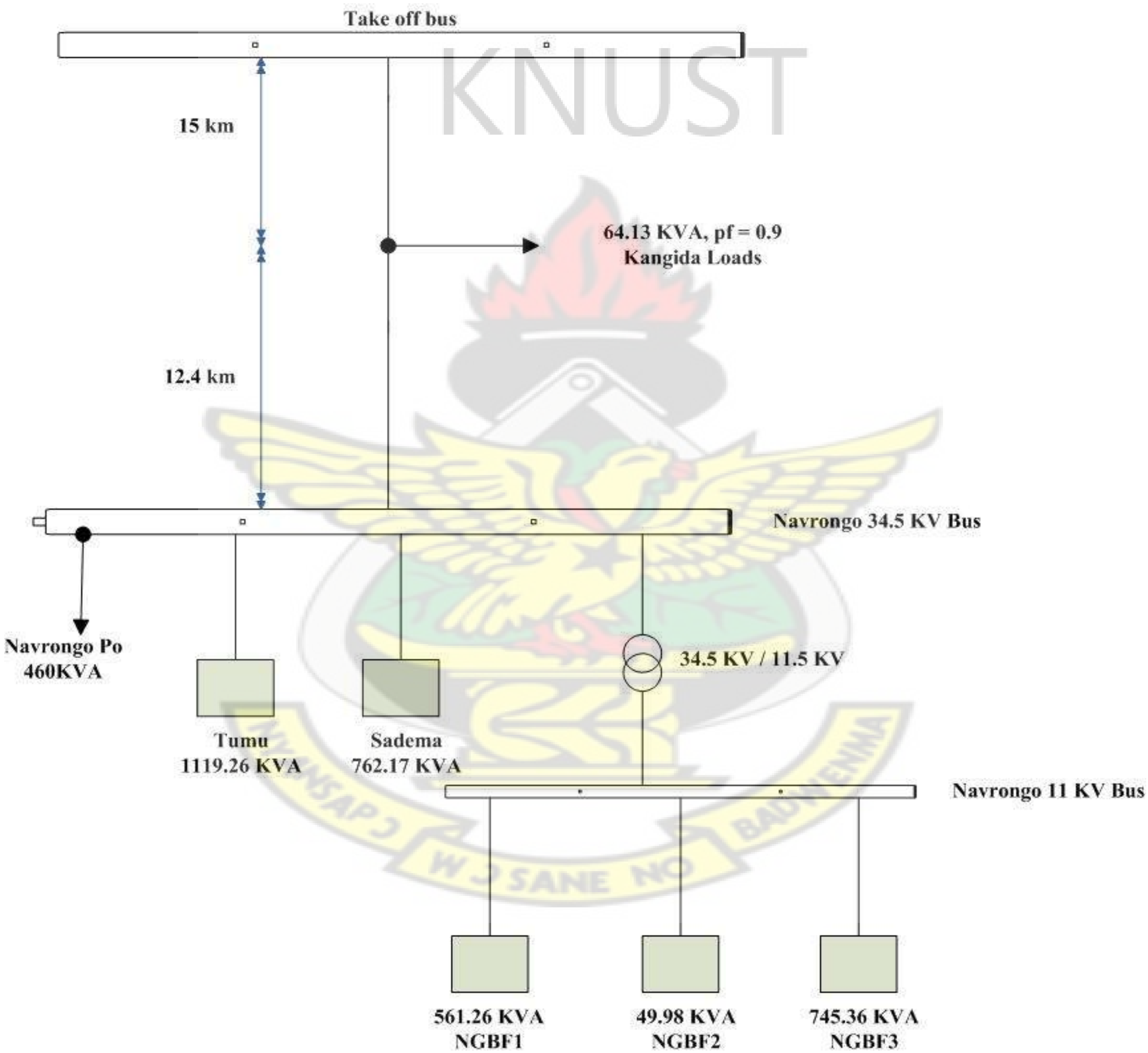


Figure 5.4: Single Line Diagram of Navrongo Network, VRA

5.3 SOLAR PV SELECTION

The desired capacity to install has already been agreed by VRA to be 1.9MWp. The VRA selected a Solar PV from Suntech. The table below shows the detail information and electrical characteristics at STC of the panel.

Table 5.1, Data Sheet Information and Electrical Characteristics at STC of Suntech PV

Data Sheet Information and Electrical Characteristics at STC	
PV Module Manufacturer	Suntech
Model Number	STP/295-24/Vd
Maximum Power (Pmax)	295W
Optimum Operating Voltage (Vmp)	35.7 V
Optimum Operating Current (Imp)	8.27 A
Module Efficiency	15.20%
Short Circuit Current (Isc)	8.57 A
Open Circuit Voltage (Voc)	45.1 V
Operating Module Temperature	$-40\ ^0C\ to + 85\ ^0C$
Power Tolerance	0 / +5%
Maximum Series Fuse Rating	20A

Number of Modules for a PV generator

$$P_{o(Array)} = P_{mmp}\ x\ N_m \qquad (8)$$

$P_{o(Array)}$ = peak power of the array

P_{mmp} = Normal power

N_m = number of modules

$$1.9\ M = 295\ x\ N_m$$

The number of number will therefore be equal to 6440.67.A little over 6440 PV modules were used to ensure that the total output power was 1.9 MWp. The performance ratio (PR) after a series of tests indicates over 90%.

5.4 INVERTER SELECTION

Since inverter is one of the most essential components of grid connected systems, the Authority carefully selected 500 kW on-grid inverter from GUANYA Powers. For the purpose of this project four of the inverter would be needed for the 1.9MWp generation. The table below shows the detail information and electrical characteristics of the selected inverter.

Table 5.2: Data Sheet Information and Electrical Characteristics at STC of GUANYA Inverter

Data Sheet Information and Electrical Characteristics	
Name of Manufacturer	GUANYA Power
Inverter Type	GSC-500KTT-TV
Output Rated Power	500 kW
European Efficiency (Weighted Average Efficiency)	> 97.5%
Maximum Efficiency	> 97.5%
10% Output Rated Power	> 90%
Maximum DC Input Voltage	DC 900 V
MPPT Voltage range	DC 440 – 850 V
Maximum DC Input Current	1200 A
Loops of DC Input	8
Output Rated Voltage	AC 415 V
Output Voltage Range	AC 330 – AC460 V
Output Frequency Range	44-55 Hz
Power factor	0.9 leading ~0.8 lagging
Maximum AC output Current	765 A
Total Harmonic Distortion	< 3%
Operation loss	<1500 W
Night Power loss	<80 W

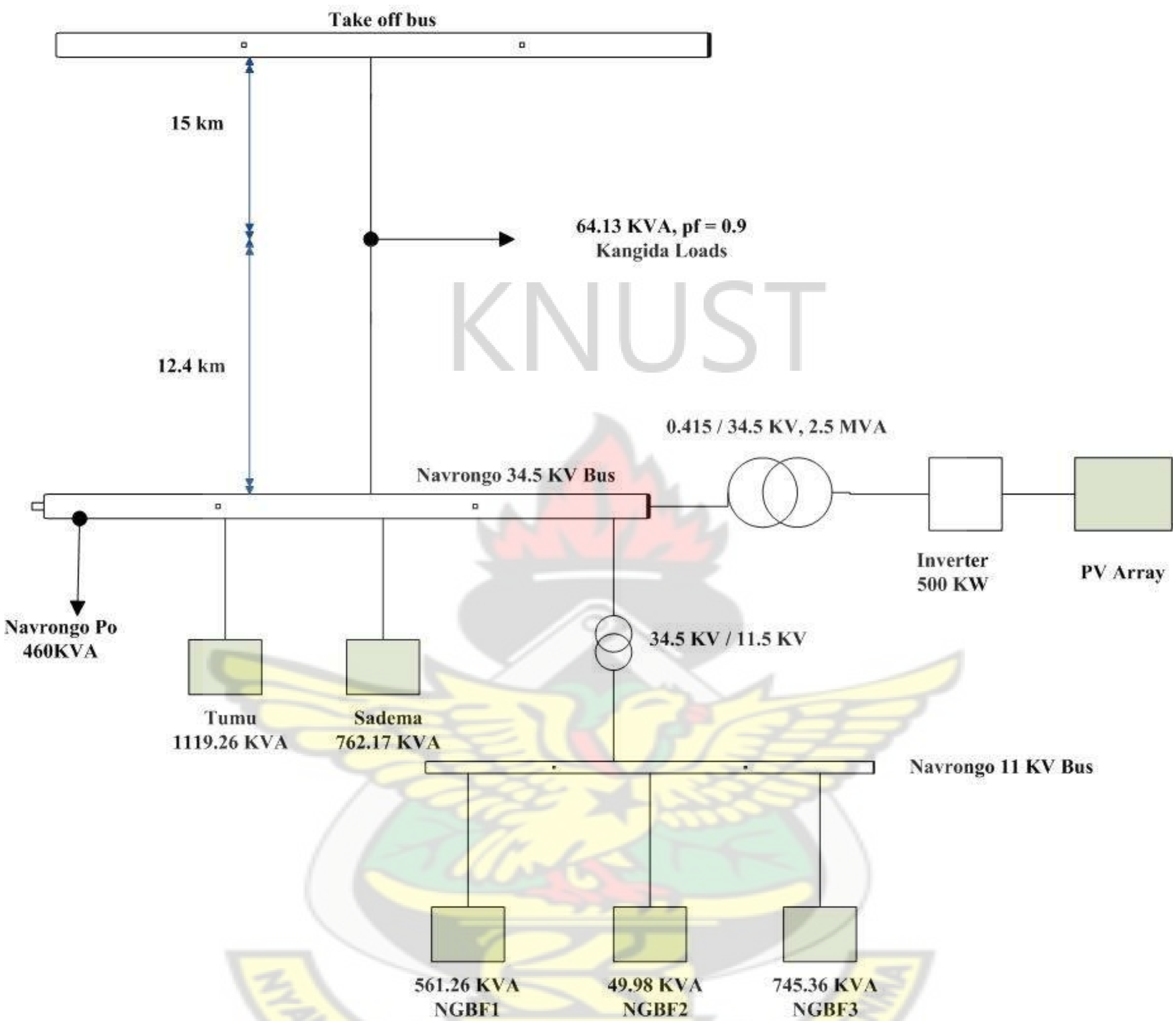
5.5 TRANSFORMER SELECTION

A 0.415/34.5 kV, 2.5 MVA step-up transformer from Baoding Tianwei Group Tebian Electric Company limited is selected for this project. The detail information of the transformer is shown in the table below.

Table 5.3, Data Sheet Information and Electrical Characteristics at STC of Baoding Transformer

Data Sheet Information and Electrical Characteristics	
Name of Manufacturer	Baoding Tianwei Group Tebian Electric CO. LTD.
Standard in force	IEC
Number of Windings	2
Rated Frequency	50.0 Hz
Rated Power	2.5 MVA
Rated Voltage MV windings	34.5 kV
Rated Voltage LV windings	0.415 kV
Voltage Ratio and Tapping	$0.415 \pm 2\ x\ 2.5\%\ /34.5\ kV$
Regulation	$\pm 2\ taps\ of\ each\ 2.5\%$
MV winding	Delta
MV winding	Star with external neutral
MV/LV	Dyn11
Short Circuit power of feeding system (MVA) - MV - LV	Infinite 2000 MVA
No Load Losses at Rated Voltage and Frequency	2.4 kW
No Load Current on 2.5 MVA Base at rated Voltage and Frequency	0.6 %

5.6 SINGLE LINE DIAGRAM WITH THE SOLAR PV INJECTION



The Figure 5.5 shows the single line diagram with of solar PV injection at the Navrongo 34.5 kV

5.7 MODELING AND SIMULATION

The Electric Power Research Institute (EPRI) developed Open Distribution System Simulation (OpenDSS) as a comprehensive electrical system simulation tool for electric utility distribution systems. The OpenDSS program has been used for distribution planning and analysis, general multi-phase AC circuit analysis, analysis of distributed generation interconnections, annual load and generation simulations, risk-based distribution planning studies, probabilistic planning studies, solar PV system simulation, wind plant simulations and other analysis. [54]

5.7.1 Structure of OpenDss

OpenDSS is a comprehensive and open-source electrical system simulation tool for electric utility distribution systems. The software can be executable as stand-alone or a COM DLL designed to be driven from a variety of existing platforms. The structure of the software incorporates Scripts, COM interface Scripts Results, user written Dynamic Link Library and the Main Simulation Engine. The COM interface provides direct access to the text-base command interface. [54]

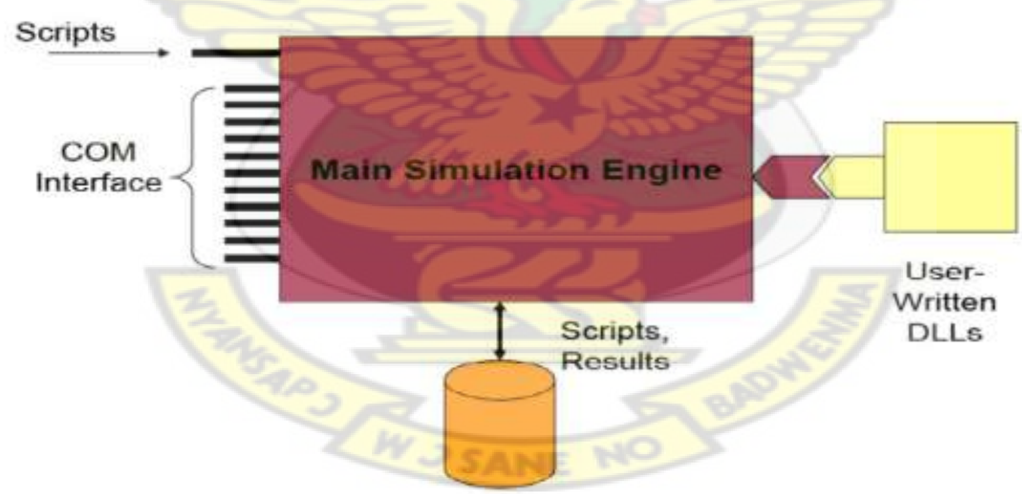


Figure 5.6: The Structure of OpenDSS [54]

5.7.2 OpenDSS PV System Element Model

The Electric Power Research Institute has built on the version of OpenDSS from time to time. This present version (7.4.1) of the model is useful, efficient and quick for simulations. The model works on the assumption that the inverter is able to find the max power point (mpp) of the panel quickly and this makes modeling of the individual components (PV panel and inverter) very simple. Figure 5.7 shows the Block diagram of the PV System Element Model. [54]

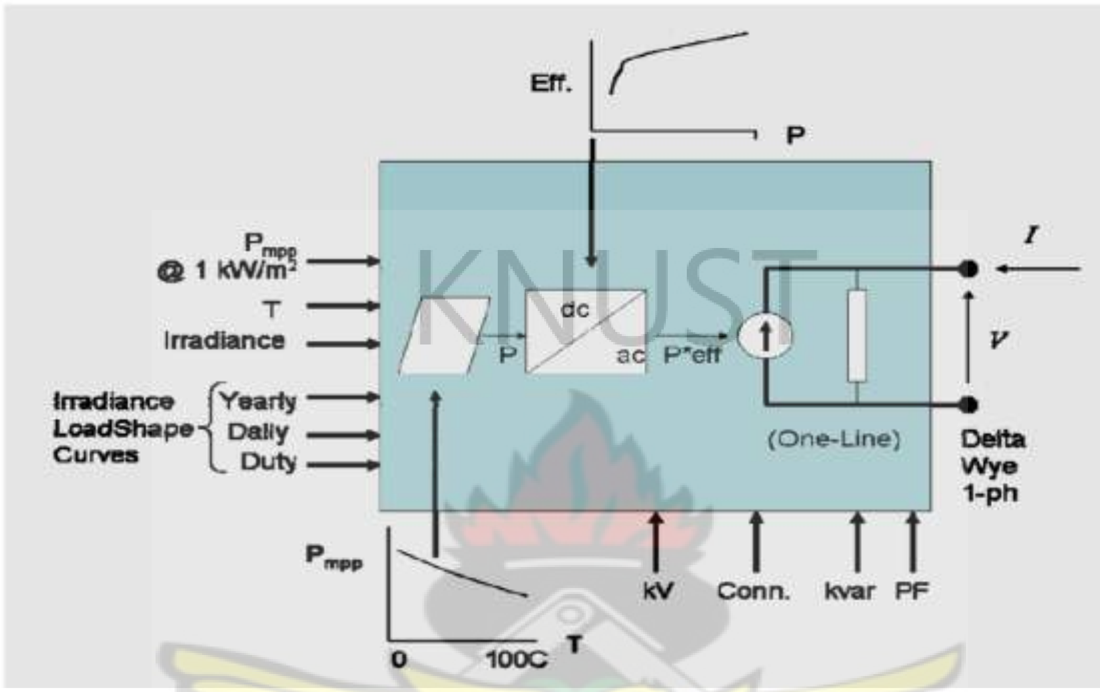


Figure 5.7: Block Diagram of the PVSystem Element Mode

Reactive power is specified separately from the active power and may be specified as either fixed kVar values or a fixed power factor value. If the PF property is specified, the model holds a constant output power factor until the PF property is changed (default mode). If the kVar property is specified, the inverter is assumed to attempt to hold that value despite the present value of the panel power. The actual kVar output is dropped if the rated kVA of the inverter is exceeded. [54]

The PV System model uses X-Ycurve objects to describe certain characteristics of the PV panels and inverters. X-Ycurve objects are new with this version of OpenDSS. One may enter x-y curves as either an array of points or as separate arrays of x and y values. [54]

5.8 MODELING SCRIPT AT 500 kW PV PENETRATION

Refer to Appendix I

CHAPTER SIX

6.0 RESULTS AND ANALYSES

The results of the simulation will be analyzed and discussed in this chapter. The total active load of the Navrongo network is 3.502 MW and the output rated power of the inverter is 500 kW, hence the injection of 500 kW represent 14% of the active load. The penetration of the solar was from 500 kW (represent 14%) to 3.5 MW (represent 100%). The simulations were done at various penetration levels for voltage, power losses and total harmonic distortion.

6.1 Voltage Variation at Various Penetration Level

The table 5.5 shows the simulation results of line to line voltage at various penetration levels (500 kW to 3.5 MW) from 0:00 to 23:00 GMT.

Table 6.1 Voltages at Navrongo Bus 34.5 kV at various penetration scenarios

Time (Hr)	Solar Irradiance(pu)	Temp (^{0}C)	Navrongo 34.5kV Bus (kV) @ 14%	Navrongo 34.5 kV Bus (kV) @28%	Navrongo 34.5 kV Bus (kV) @57%	Navrongo 34.5 kV Bus (kV) @ 85%	Navrongo 34.5 kV Bus (kV) @100%
00.00	0.00	29	33.68	33.68	33.68	33.68	33.68
01.00	0.00	28	33.68	33.68	33.68	33.68	33.68
02.00	0.00	27	33.68	33.68	33.68	33.68	33.68
03.00	0.00	27	33.68	33.68	33.68	33.68	33.68
04.00	0.00	26	33.68	33.68	33.68	33.68	33.68
05.00	0.00	25	33.68	33.68	33.68	33.68	33.68
06.00	0.00	27	33.68	33.68	33.68	33.68	33.68
07.00	0.28	28	33.71	33.75	33.82	33.89	33.92
08.00	0.45	30	33.73	33.79	33.90	34.02	34.07
09.00	0.75	31	33.77	33.87	34.05	34.24	34.33
10.00	0.84	33	33.79	33.89	34.09	34.30	34.39
11.00	0.97	33	33.80	33.92	34.14	34.70	34.48
12.00	1.00	35	33.79	33.90	34.11	34.33	34.43
13.00	0.94	36	33.80	33.91	34.13	34.36	34.47
14.00	0.87	37	33.79	33.90	34.10	34.30	34.41
15.00	0.83	40	33.78	33.88	34.07	34.28	34.37
16.00	0.60	39	33.71	33.83	33.97	34.12	34.18
17.00	0.30	37	33.71	33.75	33.82	33.90	33.93
18.00	0.00	35	33.68	33.68	33.68	33.68	33.68
19.00	0.00	32	33.68	33.68	33.68	33.68	33.68

20.00	0.00	30	33.68	33.68	33.68	33.68	33.68
21.00	0.00	30	33.68	33.68	33.68	33.68	33.68
22.00	0.00	31	33.68	33.68	33.68	33.68	33.68
23.00	0.00	29	33.68	33.68	33.68	33.68	33.68

6.1.1 Analysis of the Results

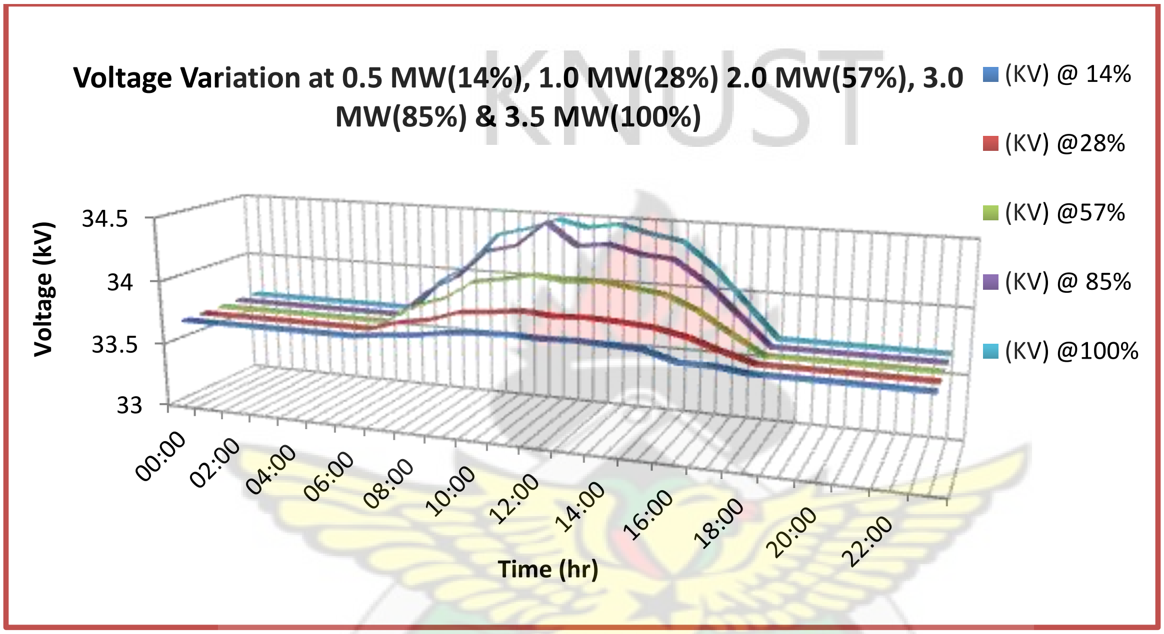


Figure 5.8: A Graph of Voltage Variation

Figure 5.8 represent a graph of Voltage Variation at 0.5 MW (14%), 1.0 MW (28%), 2 MW (57%), 3.0 MW (85%) & 3.5 MW (100%). The voltage was steady during the hour of 00:00 to 06:00 but it shown a gradual increase when the PV is injected from the hour of 07:00 at 0.28 kWh/m²/d (pu) of solar irradiance and 28 ^{0}C of temperature. The voltage rises from 33.68 kV (without solar PV) for all penetration levels. The increase was 33.92 kV, 34.14 kV and 34.48 kV for 1.0 MW (28%), 2.0 MW (57%) & 3.5 MW (100%) respectively. The voltage rise is also directly proportional to the penetration level hence 3.5 MW (100%) having the highest voltage rise at 0.97 kWh/m²/d (pu)

The main reason for this increase or rise in voltage is that solar inverter pushes electricity back out to the grid by slightly raising its voltage above the source grid voltage. The result of this is the further away the transformer, the higher the voltage drop and thus the inverter has to increase its voltage to push the energy back out to the grid. This is one of the main concerns to distribution companies regarding solar photovoltaic (PV) grid-connected. The voltage profile indicates that the voltage still remains within the statutory limit 36.225 kV.

6.2 Total Power Losses in Navrongo 34.5 system at various Penetration levels

The table 5.6 shows the simulation results total power losses at various penetration levels (500 kW to 3.5 MW) from 0:00 to 23:00 GMT.

Table 6.2 Total Power Losses at Navrongo Bus 34.5KV at various Penetration levels

Time (Hr)	**Solar Irradiance (pu)**	**Temp (^{0}C)**	**Navrongo 34.5 kV Bus (kV) @14%**	**Navrongo 34.5 kV Bus (kV) @28%**	**Navrongo 34.5 kV Bus(kV) @57%**	**Navrongo 34.5kV Bus (kV) @85%**	**Navrongo 34.5 kV Bus (kV) @100%**
00.00	0.00	29	1.47	1.47	1.47	1.47	1.47
01.00	0.00	28	1.47	1.47	1.47	1.47	1.47
02.00	0.00	27	1.47	1.47	1.47	1.47	1.47
03.00	0.00	27	1.47	1.47	1.47	1.47	1.47
04.00	0.00	26	1.47	1.47	1.47	1.47	1.47
05.00	0.00	25	1.47	1.47	1.47	1.47	1.47
06.00	0.00	27	1.47	1.47	1.47	1.47	1.47
07.00	0.28	28	1.37	1.28	1.13	0.98	0.92
08.00	0.45	30	1.32	1.18	0.99	0.79	0.72
09.00	0.75	31	1.22	1.04	0.85	0.65	0.64
10.00	0.84	33	1.20	1.01	0.84	0.66	0.68
11.00	0.97	33	1.16	0.96	0.84	0.71	0.78
12.00	1.00	35	1.16	0.96	0.85	0.71	0.78
13.00	0.94	36	1.17	0.97	0.84	0.69	0.74
14.00	0.87	37	1.19	1.00	0.84	0.66	0.69
15.00	0.83	40	1.12	1.02	0.84	0.65	0.66
16.00	0.60	39	1.27	1.12	0.91	0.69	0.64
17.00	0.30	37	1.37	1.28	1.12	0.96	0.90
18.00	0.00	35	1.47	1.47	1.47	1.47	1.47
19.00	0.00	32	1.47	1.47	1.47	1.47	1.47
20.00	0.00	30	1.47	1.47	1.47	1.47	1.47
21.00	0.00	30	1.47	1.47	1.47	1.47	1.47
22.00	0.00	31	1.47	1.47	1.47	1.47	1.47
23.00	0.00	29	1.47	1.47	1.47	1.47	1.47

6.2.1 Analysis of the Results

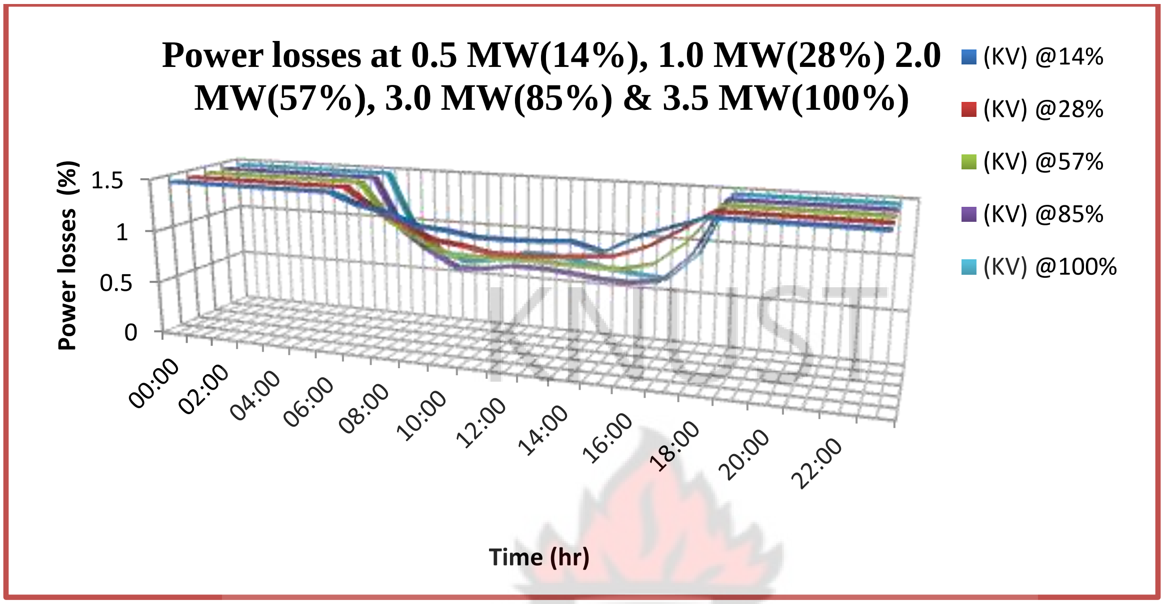


Figure 5.9: A Graph of Power Loss

Figure 5.9 represent a graph of Power Losses at 0.5 MW (14%), 1.0 MW (28%), 2 MW (57%), 3.0 MW (85%) & 3.5 MW (100%). The Power Loss decreased from 07:00 to 17:00 GMT. Without PV injection the Power Losses were steady from 00:00 to 06:00 but shown a gradual decrease when the Solar PV was injected at the hour of 07:00 at 0.28kWh/m²/d (pu) of solar irradiance and 28 ^{0}C of temperature. The Total Power loss decreases from 1.47% at all penetration levels to 1.16%, 0.96%, 0.84%, 0.65% and 0.64 for 0.5 MW (14%), 1.0 MW (28%), 2 MW (57%), 3.0 MW (85%) & 3.5 MW (100%) respectively.

This variation in the system percentage loss is due to the varying values of irradiance and temperature. Most importantly the decrease in power losses is as a result of decrease in power flow from the take off bus. The distance between the take off bus and the Navrongo 34.5 kV bus is about 27 km, hence injecting Solar PV at the Navrongo reduces power flow from the take off bus and therefore reducing the transmission line losses and other circuit losses.

6.3 Total Harmonic Distortion at Navrongo Bus 34.5 kV at various Penetration levels

The table 5.7 shows the simulation results total Harmonic Distortion at 0.5 MW (14%), 1.0 MW (28%), 2 MW (57%), 3.0 MW (85%) & 3.5 MW (100%) from 0:00 to 23:00 GMT.

Table 6.3: Total Harmonic Distortion at Navrongo Bus 34.5 kV at various penetration levels

Time (Hrs)	Temp (^{0}C)	Irradiance (pu)	THD @ 14 %	THD @ 28 %	THD @ 57%	THD at 85%	THD @ 100 %
0:00	29	0.00	2.98	3.07	5.59	6.77	7.89
1:00	28	0.00	2.98	3.07	5.59	6.77	7.89
2:00	27	0.00	2.98	3.07	5.59	6.77	7.89
3:00	27	0.00	2.98	3.07	5.59	6.77	7.89
4:00	26	0.00	2.98	3.07	5.59	6.77	7.89
5:00	25	0.00	2.98	3.07	5.59	6.77	7.89
6:00	27	0.00	2.98	3.07	5.59	6.77	7.89
7:00	28	0.28	3.03	3.18	5.95	6.91	8.35
8:00	30	0.45	3.12	3.32	6.2	7.08	8.73
9:00	31	0.75	3.37	3.59	6.68	7.13	8.97
10:00	33	0.84	3.43	3.67	6.85	7.45	9.17
11:00	33	0.97	3.60	3.78	7.01	7.89	9.38
12:00	35	1.00	3.69	3.72	6.92	8.12	9.67
13:00	36	0.94	3.74	3.76	6.98	8.46	9.73
14:00	37	0.87	3.67	3.68	6.85	8.37	9.53
15:00	40	0.83	3.59	3.63	6.76	8.23	9.23
16:00	39	0.60	3.28	3.43	6.4	7.94	8.79
17:00	37	0.30	3.17	3.19	5.71	7.16	8.15
18:00	35	0.00	2.98	3.07	5.59	6.77	7.89
19:00	32	0.00	2.98	3.07	5.59	6.77	7.89
20:00	30	0.00	2.98	3.07	5.59	6.77	7.89
21:00	30	0.00	2.98	3.07	5.59	6.77	7.89
22:00	31	0.00	2.98	3.07	5.59	6.77	7.89
23:00	29	0.00	2.98	3.07	5.59	6.77	7.89

6.3.1 Analysis of the Results

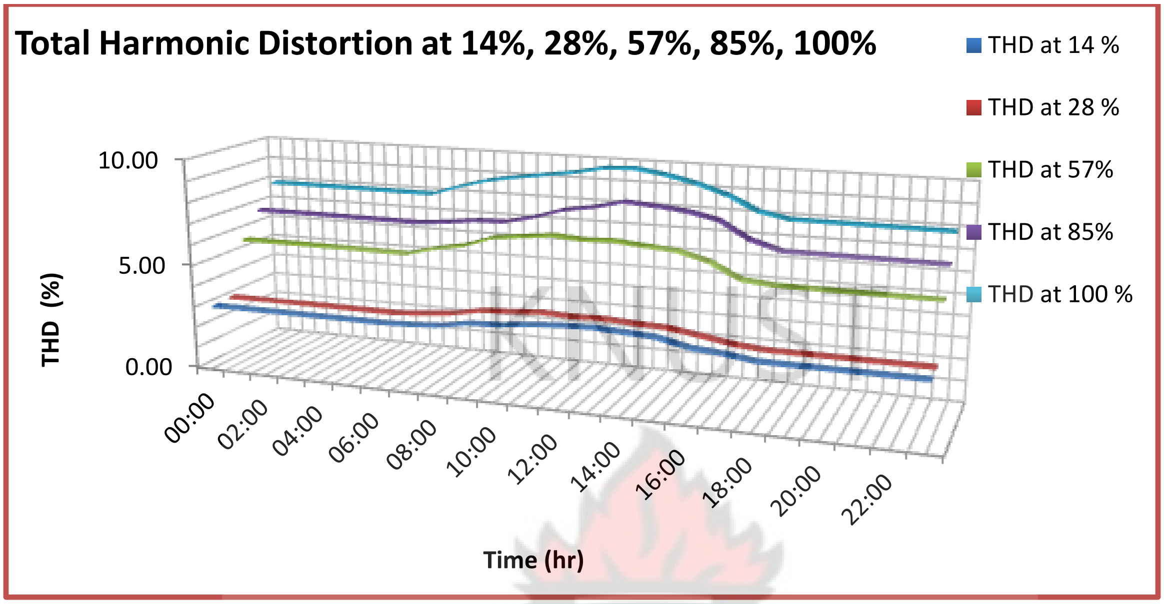


Figure 5.10: A Graph of Total Harmonic Distortion

The power electronic components in the PV inverters give rise to harmonics in the PV system. Figure 5.10 shows a graphical presentation of Total Harmonic Distortion (THD) at various penetration levels. All the penetration levels show rise in total harmonic distortion. The highest total harmonic distortion for 14%, 28%, 57%, 85% and 100% penetrations were 3.60%, 3.78%, 7.01%, 7.89% and 9.38%. In Europe, the standard 61400- 21 recommends to apply the standard 61000-3-6 valid for polluting loads requiring the current THD smaller than 6-8 % depending on the type of network.

In countries like Australia and Greece, the total harmonic distortion should not exceed 5%. This figure is different in Germany, which gives a harmonic distortion allowance of up to 8 % for inverter current up to the 50th harmonic. From the result, 57% (2.0 MW) and above violate the THD limitation.

In general, a harmonic problem can be defined as a particular disturbance, which is created by the presence of non-linear components in the electrical system that determines a permanent modification of the voltage and current sinusoidal wave shapes in terms of sinusoidal components at a frequency different from the fundamental.

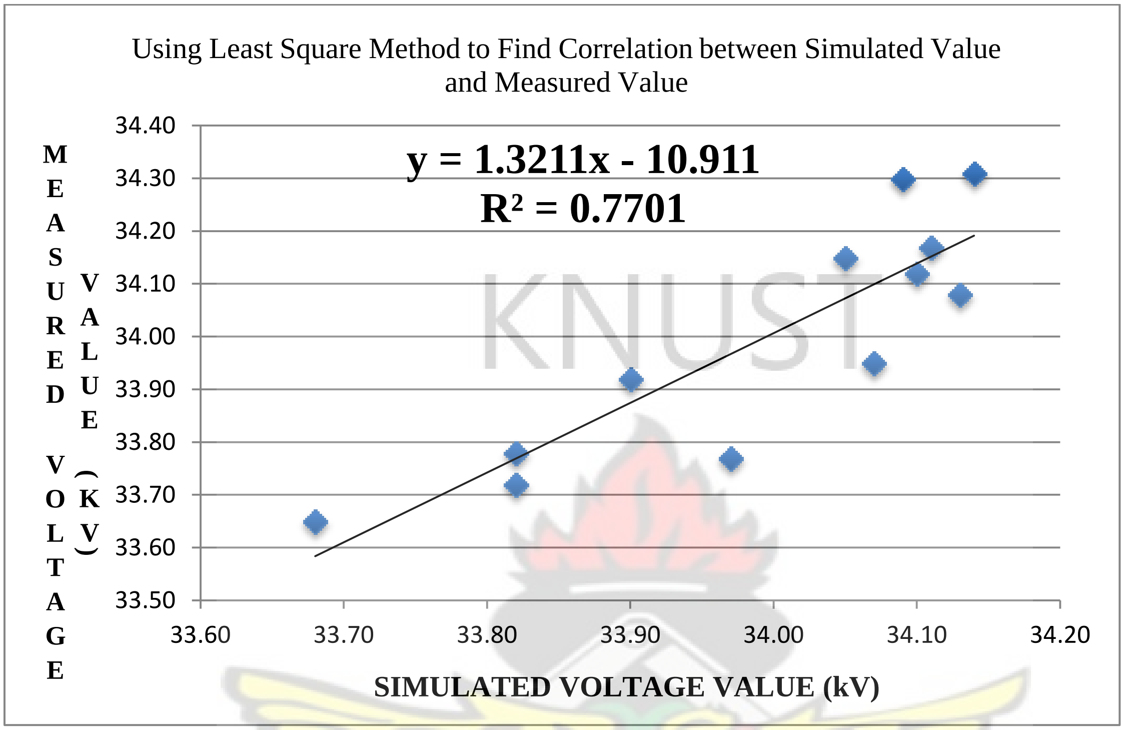
6.4 Validation of Simulated Results with Measured Data

Simulated voltage results were validated with the measured results on site since the project is in operation now. Using the Least Square Methods, the correlation between simulated and measured values was determined.

Table 6.4: Simulated values of Voltage at 57% (2.0 MW) versus Measured value for the month of June. (For sampled measured values refer to Appendix II)

Time	Simulated	Measured
6:00	33.68	33.65
7:00	33.82	33.72
8:00	33.9	33.92
9:00	34.05	34.15
10:00	34.09	34.3
11:00	34.14	34.31
12:00	34.11	34.17
13:00	34.13	34.08
14:00	34.1	34.12
15:00	34.07	33.95
16:00	33.97	33.77
17:00	33.82	33.78

Figure 5.11: Using Least Square Method to Find Correlation between Simulated Value and Measured Value



The correlation coefficient (R^2) is always a number between -1 and 1. Values of R^2 that are close to 1 indicate reliable formula. The value of R^2 obtained is a good hence we can be able to predict the actual voltage will correspond to any simulated value.

CHAPTER SEVEN

7.0 CONCLUSION

The research has investigated and identified the technical challenges that exist when integrating utility-scale solar PV into transmission grid to be Voltage Rise, Voltage Stability, Harmonics, Islanding and Power Quality.

The research modeled and simulated using OpenDSS software the 2.0MWp PV of the Volta River Authority's Renewable Energy Development Project (REDP) at Navrongo at various penetration levels. The results for voltage variations, power losses and total harmonic distortions have been analyzed and discussed.

It can be concluded from the simulated results and analysis the voltage soars from 33.68 KV (without solar PV) for all penetration levels to 33.92 kV, 34.14 kV and 34.48 kV for 1MW (28%), 2MW (57%) & 3.5MW (100%) respectively. The voltage rise is also directly proportional to the penetration level hence 3.5 MW (100%) having the highest voltage rise at 0.97 kWh/m²/d (pu). The voltage profile indicates that the voltage still remains within the statutory limit 36.225 kV.

The Total Power loss decreases from 1.47% at all penetration levels to 1.16%, 0.96%, 0.84%, 0.65% and 0.64 for 0.5 MW (14%), 1.0 MW (28%), 2 MW (57%), 3.0 MW (85%) & 3.5 MW (100%) respectively. Total harmonic distortion rise at all penetration levels. The highest total harmonic distortion for 14%, 28%, 57%, 85% and 100% penetrations were 0.97%, 3.60%, 3.78%, 7.01%, 7.89% and 9.38%.

7.1 RECOMMENDATIONS

- Its recommended that Dynamic/Static Var Compensator and Static Synchronous Compensator should be used to control the total harmonic distortion which is above the normal (US) for 2MWp and above penetration
- The Energy Commission should outline code and standards for integrating RE into the Ghanaian transmission grid
- Study should be conducted to investigate Islanding and reserve power flow, which this paper couldn't accomplish because of the limitation of the software.

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APPENDICES

APPENDIX I

MODELING SCRIPT AT 500 KW PENETRATION

The script below shows how the 500 KWp was modeled and simulated. Clear

! Clears all circuit element definitions from the DSS. This statement is recommended at the beginning of all Master files for defining DSS circuits.

Set DefaultBaseFrequency=50

!Default Base Frequency value when first installed is 60 Hz. This is different from the default base frequency of VRA hence the frequency must be set to 50 HZ

New Circuit.NAVRONGO

! This function makes a new circuit object and returns the Circuit interface to the active Circuit. In our case the circuit is name as NAVRONGO.

~ BasekV=34.5   Bus1=Take_off_bus_pu=1.0   MVASC3=5000000   5000000

! The VSOURCE object created by the New Circuit command must be edited and in our case it is 34.5 KV

! The new circuit elements (Lines, transformers and the loads) must be defined.

! Lines Definition

New line.XLN-0248   Bus1=Take_off_BUS Bus2=Kangida_Node R1=0.1375 X1=.41 Length=15 units = km

! The line between the take off bus and Kangida Node, 15 km.

New line.XLN-0264   Bus1=Kangida_Node Bus2=Navrongo_34_5_KV_BUS R1=0.1375 X1=.41   Length=12.4 units = km

The line between the Kangida Node and Navrongo 34.5 Bus, 12.5 km.

! R1 = Positive-Sequence resistance, ohms per unit length, X1 = Positive-Sequence reactance, ohms per unit length. XLN-0248 and XLN-0264 are the names of the lines thus from takeoff bus to KANGIDA NODE and from KANGIDA NODE to NAVRONGO 34.5KV Bus

! Transformers Definition

New Transformer.Navrongo kVAs= [3000 3000] XHL=7 PPM=0

~ Wdg=1 kV=34.5 Bus=Navrongo_34_5_KV_BUS Tap=1

~ Wdg=2 kV=11 Bus=Navrongo_11_KV_BUS

~ %R=.68

New Transformer.PVSTEPUPkVAs=[2500 2500] XHL=7 PPM=0 ~ Wdg=1 R=0 kV=.415 Bus=PVbus Tap=1

~ Wdg=2 R=0 kV=34.4 Bus=Navrongo_34_5_KV_BUS ~ %R=0.7

! Wdg= Integer representing the winding which will become the active winding for subsequent, data. XHL = Percent reactance high to low (winding 1 to winding 2).

Ppm_Antifloat = Parts per million for anti floating reactance to be connected from each terminal to ground. Default is 1. That is, the diagonal of the primitive Y matrix is increased by a factor of 1.000001. Set this to zero if you don’t need it and the resulting impedance to ground is affecting the results

! Load Definition

New Load.Lumped_kangida Bus1=Kangida_Node kV=34.5 kVA=64.13 pf=.9

New Load.Navrongo_po Bus1=Navrongo_34_5_KV_BUS kV=34.5 kVA=460 pf=.9

New Load.Tumu Bus1=Navrongo_34_5_KV_BUS   kV=34.5   kVA=1119.26 pf=.98

New Load.sandema Bus1=Navrongo_34_5_KV_BUS   kV=34.5   kVA=762.17 pf=.97

New Load.NGBF1 Bus1=Navrongo_11_KV_BUS   kV=11   kVA=561.26 pf=.88

New Load.NGBF2 Bus1=Navrongo_11_KV_BUS   kV=11   kVA=49.98 pf=.89

New Load.NGBF3 Bus1=Navrongo_11_KV_BUS   kV=11   kVA=745.36 pf=.88

! Solar PV Definition

New XYCurve.MyPvs Tnpts=4 xarray= [0 25 75 100] yarray=[1.2 1.0 0.8 0.6]

// The PVsystem model uses XYcurve objects to describe certain characteristics of the PV panels and inverters. An average Pmpp for the panel at 1 kW/m2 irradiance at a constant panel temperature of 250C, x-array = temperature and y-array=power (per unit)

// P-T curve is per unit of rated Pmpp vs temperature.

// efficiency curve is per unit eff vs per unit power

New XYCurve.MyEff npts=4 xarray=[.1 .2 .4 1.0] yarray=[.86 .9 .93 .97]

// per unit irradiance curve, x-array = per unit power and y-array = efficiency

New Loadshape.MyIrrad npts=24 interval=1 mult=[0 0 0 0 0 0 0 .28 .45 .75 .84 .97 1 .94 .87 .83 .6 .3 0 0 0 0 0 0]

// 24-hr solar irradiance of navrongo in per unit.

New Tshape.MyTemp npts=24 interval=1 temp= [29 28 27 27 26 25 27 28 30 31 33 33 35 36 37 40 39 37 35 32 30 30 31 29]

// 24hr temperature of Navrongo, renewable energy policy, Meteorologisk institute // **** plot tshape object=mytemp

New PVSystem.PV1 phases=3 bus1=PVbus kV=.415 kVA=500 irrad=.9 Pmpp=500 ~ temperature=35 PF=.9 effcurve=Myeff P-TCurve=MyPvsT

~ Daily=MyIrradTDaily=MyTemp

// Solar PV defined, irrad = irradiance and temperature will change for each hour within the 24hrs.

Solve

APPENDIX II

Daily Report of Navrongo Solar PV Plant

Date: 2015-08-06

Time	34.5kV Bus Voltage						Outgoing			the Main Circuit			Branches			LV side of the M Trfm			M Trfm	M Trfm	Envir.	Global
	A	B	C	AB	AC	BC	Current	Active	Idle	Current	Active	Idle	Current	Active	Idle	Current	Active	Idle	Oil T	Coil T	Temp.	Radiat
	kV	kV	kV	kV	kV	kV	A	kW	kVar	A	kW	kVar	A	kW	kVar	A	kW	kVar	℃	℃	℃	w/m2
6am	19.08	18.9	18.76	33.05	32.75	32.71	6.64	394.27	-38.06	6.71	397.31	-32.73				603.52	409.17	-26.3	34.97	37.28	28.8	205
7am	19.17	18.98	18.83	33.1	32.76	32.74	8.09	478.75	-36.53	8.23	481.04	-35.77				725.56	496.31	-19.84	35.18	37.29	29.2	276
8am																						
9am	19.42	19.22	19.04	33.5	33.1	33.15	14.55	857.51	-32.49	14.58	860.84	-35.82				1283.69	878.26	0	37.18	37.76	31	542
10am	19.21	19.05	18.89	33.37	32.91	32.92	12.88	765.98	-10.42	12.91	768.74	-15.22				1098.25	785.46	9.5	40.56	39.82	32.5	703
11am	19.52	19.34	19.17	33.76	33.2	33.27	20.61	1221.42	-59.85	20.65	1227.71	-54.8				1794.63	1256.74	0	43.41	41.56	34.2	786
12am	19.57	19.22	19.01	33.63	33.19	33.18	21.78	1286.31	-61.65	21.62	1284.79	-60.89				1876	1307.16	0	46.36	44.14	35.2	803
13pm	19.51	18.34	19.13	33.84	33.37	33.33	20.43	1217.05	-60.13	20.49	1223.14	-63.17				1777.73	1250.24	0	48.47	46.83	36.4	876
14pm	19.2	19.04	18.82	33.25	32.81	32.81	12.82	738.3	-30.45	11.76	685.78	-30.45				1040.61	758.43	0	48.1	47.52	37.7	778
15pm	19.26	19.06	18.89	33.29	32.83	32.87	14.66	857.04	-40.34	15.48	860.8	-40.34				1289.06	868.76	-8.77	48.68	48.78	37.9	601
16pm	18.95	18.74	18.55	32.76	32.36	32.48	8.66	498.54	-31.97	8.53	493.98	-23.6				734.77	497.58	-12.42	47.26	49.05	37.3	393
17pm	19.35	19.15	18.94	33.46	32.94	32.93	3.6	229.34	-27.4	4.06	242.02	-28.16				369.14	246.96	-27.03	45.83	47.52	37.02	185
18pm																						
19pm																						

Time	#1 Inverter				#2 Inverter				#3 Inverter				#4 Inverter				#5 Inverter			
	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.
6am	398.84	111.96	83.97	33.09	396.84	81.97	64.97	28.89	399.84	110.96	83.97	34.89	396.84	114.96	86.97	34.29	391.85	145.94	93.96	31.29
7am	398.84	141.94	102.96	33.09	396.84	124.95	94.96	28.29	398.84	138.98	103.96	34.89	396.84	147.94	107.96	33.69	391.85	176.93	115.95	31.29
8am																				
9am					396.84	280.89	205.92	29.49	399.84	290.89	207.92	35.49	397.84	298.88	216.92	34.89	406.84	384.85	262.9	32.49
10am					397.84	352.86	257.9	31.29	399.84	368.9	262.9	36.59	398.84	376.85	274.89	35.99	413.84	402.84	285.89	33.09
11am					398.84	409.84	303.88	31.89	401.84	417.83	299.88	37.19	398.84	431.83	309.88	36.59	417.84	529.79	373.85	33.09
12am					398.84	434.83	312.88	32.49	400.84	431.83	311.88	38.39	399.84	440.83	316.88	37.79	420.84	544.79	388.85	34.29
13pm					398.84	407.84	297.88	33.69	401.84	410.84	294.88	38.58	398.84	417.84	299.88	38.98	418.84	509.8	360.86	34.89
14pm					397.84	336.87	259.9	33.69	399.84	282.89	196.92	39.58	397.84	262.9	205.91	39.58	410.84	474.81	327.87	35.49
15pm					395.85	311.88	205.92	34.29	397.84	307.88	204.83	40.18	396.84	317.88	210.92	40.18	405.84	357.97	257.9	35.99
16pm					395.85	147.94	111.96	34.29	398.84	151.94	111.96	40.18	396.84	153.94	115.95	40.18	389.85	220.91	143.94	35.99
17pm									399.84	65.97	53.98	39.58	397.84	65.97	53.98	39.58	393.85	108.96	69.97	35.59
18pm																				
19pm																	Daily Delieved Energy		9120kwh	

Outgoing			LV Side			Site Consumed								
6am	18pm	Qty.	6am	18pm	Qty.	6am	18pm	Qty.	Current	-0.94	F6S Pressure	0.55	Daily Generated Energy	9380.09kwh
									Battery Voltage	132.92	415V Voltage	406.64	Accum. Delivered Energy	548460kwh
179.78	182.82	9120	189.98	195.21	9526.01	41.77	42.28	56.08	Bus Voltage	124.76	System Frequency	49.96	Accu. Generated Energy	562255.51kwh

Supervisor: LIANG Operator: DOE

Daily Report of Navrongo Solar PV Plant

Date: 15/06/15

Time	34.5kV Bus Voltage						Outgoing			the Main Circuit			Branches			LV side of the M Trfm			M Trfm	M Trfm	Envir.	Global
	A	B	C	AB	AC	BC	Current	Active	Idle	Current	Active	Idle	Current	Active	Idle	Current	Active	Idle	Oil T	Coil T	Temp.	Radiat
	kV	kV	kV	kV	kV	kV	A	kW	kVar	A	kW	kVar	A	kW	kVar	A	kW	kVar	℃	℃	℃	w/m2
6am	20.32	20.22	20	35.17	34.73	34.66	0.53	20.55	23.6	0.51	20.55	24.36				51.56	24.84	25.57	33.6	36.5	25.3	11
7am	20.01	19.94	19.71	34.74	34.27	34.27	2.11	139.29	0	2.27	150.7	-8.37				223.34	160.52	0	33.23	36.76	25.8	66
8am	19.85	19.64	19.55	34.37	33.97	34	9.01	544.73	-44.91	9.08	553.34	-43.38				814.15	576.49	-32.15	34.07	36.5	27.1	259
9am	19.71	19.53	19.42	34.07	33.71	33.78	18.6	1092.23	-47.23	18.19	1080.3	-48.71				1586.7	1120.84	-8.77	35.44	36.76	28.6	478
10am	19.69	19.5	19.39	33.98	33.57	33.7	25.44	1506.28	-59.37	25.37	1504.8	-69.26				232.16	1500.09	13.15	39.5	38.03	31.1	776
11am	19.49	19.39	19.27	33.38	33.56	33.69	27.2	1646.31	-95.9	28.02	1774.4	-97.66				2642.8	1791.83	10.23	42.3	41.67	32.5	523
12am	19.66	19.53	19.45	33.91	33.47	33.56	18.16	1132.5	-61.65	24.04	1851.6	-66.2				2091.9	1753.26	8.04	46.25	44.88	33.8	855
13pm	29.63	19.42	19.33	34.03	33.64	33.66	28.24	1580.6	-92.1	23.39	1698.1	92.86				2465.6	1730.94	-13.15	48.84	47.52	34.9	787
14pm	19.51	19.3	19.2	33.71	33.3	33.42	22.03	1379.31	-53.84	22.84	1313.7	-60.41				2076.3	1363.19	6.58	49.52	50.1	37.3	833
15pm	19.54	19.33	19.22	33.73	33.35	33.29	16.9	1002.17	-41.86	17.18	1016.6	-44.15				1495.1	1048.62	0	47.73	50.1	36.5	451
16pm	19.68	18.86	18.73	32.92	32.48	32.57	14.66	855.47	-44.82	14.55	846.38	-40.06				1258.6	859.61	-10.23	47.94	49.42	37.1	449
17pm	19.11	18.88	18.73	32.82	32.31	32.39	4.58	263.59	-22.83	4.28	250.56	-22.83				380.03	243.58	-18.27	47.04	48.89	36.5	143
18pm																						
19pm																						

Time	#1 Inverter				#2 Inverter				#3 Inverter				#4 Inverter				#5 Inverter					
	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.	Voltage	Current	Active	Temp.		
6am	401.84	4	5	32.49	399.84	3	4	32.49	402.84	4	4	33.09	400.84	3	5	32.49	413.84	12	7	30.09		
7am	400.84	30.99	28.99	31.29	398.84	41.98	35.99	31.29	401.84	45.98	36.99	31.89	399.84	46.98	37.98	31.29	406.84	63.97	40.98	30.09	Daily	Total
8am	400.84	150.94	112.96	31.89	398.84	148.94	113.96	32.49	401.84	158.04	115.95	32.49	399.84	159.94	120	31.29	405.84	216.92	146.94	30.09	operat	monthly
9am	402.84	298.88	215.92	33.09	400.84	294.88	213.92	33.69	403.84	298.88	215.92	33.09	401.84	317.88	229.9	32.49	418.84	381.85	267.9	30.09	ional	operati
10am	402.84	396.84	285.89	34.89	400.84	389.85	281.89	35.49	403.84	387.85	277.89	34.29	401.84	384.85	278.9	33.69	424.83	472.82	335.87	31.29	hours	onal
11am	401.84	370.86	287.89	35.99	400.84	424.82	367.86	37.19	403.84	520.8	359.86	35.49	401.84	521.8	330.9	35.49	422.83	558.78	400.87	32.49	11Hrs	hours
12am	402.84	388.85	276.89	37.79	400.84	365.86	304.88	38.39	403.84	437.82	313.88	37.19	401.84	471.81	336.9	36.59	426.83	569.78	411.84	33.69		143
13pm	402.84	475.81	339.87	38.98	400.84	466.82	335.87	39.58	403.84	477.81	338.87	38.39	401.84	477.81	340.9	37.79	420.84	447.83	419.84	34.29		
14pm	401.84	402.84	287.84	40.18	399.84	420.84	279.89	40.78	401.84	385.85	261.6	38.98	399.84	410.84	255.9	38.98	420.84	490.81	346.86	34.89		
15pm	399.84	290.89	209.92	39.58	397.84	291.89	209.92	40.18	400.84	288.87	204.92	38.98	397.84	270.89	196.9	38.98	412.84	379.85	262.9	34.89		
16pm	398.84	215.92	156.94	39.18	396.86	201.92	148.94	40.18	398.84	203.92	148.94	39.58	396.84	206.92	150.9	39.58	392.85	273.89	177.93	35.49		
17pm	398.84	55.98	44.98	39.58	396.84	50.98	41.98	40.18	398.84	50.98	40.98	38.98	396.84	46.98	37.99	38.98	389.85	72.97	47.98	34.49		
18pm																						
19pm																	Daily Delieved Energy			11460KWH		

Outgoing			LV Side			Site Consumed								
									Current	-0.81	F6S Pressure	0.55	Daily Generated Energy	11583kwh
6am	18pm	Qty.	6am	18pm	Qty.	6am	18pm	Qty.	Battery Voltage	132.92	415V Voltage	411	Accum. Delivered Energy	598980kwh
195.9	199.94	11460	207.01	211	11619.1	44.85	46.45	64.6	Bus Voltage	124.69	System Frequency	60.19	Accu. Generated Energy	614135.51kwh

Supervisor: LIU　　　　Operator: DOE