

PERFORMANCE EVALUATION OF 620MW PHOTOVOLTAIC
SYSTEM INTEGRATED INTO AN ISLANDED NIGERIA
ELECTRIC POWER GRID

BY

IBUODINMA, SOMTOCHUKWU IFEANYICHUKWU (B.Eng)

REG NO: 20174079878

A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL
FEDERAL UNIVERSITY OF
TECHNOLOGY OWERRI.

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
AWARD OF THE DEGREE OF MASTER OF ENGINEERING (M. ENG) IN
ELECTRICAL POWER SYSTEM ENGINEERING.

JULY, 2021.

CERTIFICATION

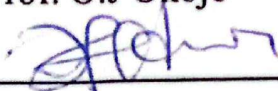
This is to certify that this thesis titled "Performance Evaluation of 620MW Photovoltaic Systems Integrated into an Islanded Nigeria Electric Power Grid" is the original work done by Ibuodinma Somtochukwu Ifeanyichukwu (20174079878) under the supervision of Engr. Prof. O. J Onojo and presented at the Department of Electrical and Electronic Engineering, Federal University of Technology, Owerri, Imo State, Nigeria in partial fulfilment of the requirements for the award of the degree, Masters of Engineering (M.Eng) in Power system Engineering.



23/6/25

Engr. Prof. O.J Onojo

Date



23/6/25

Engr. Dr. N. Chukwuchekwa

Date

(HOD, Elect. and Elect. Eng. Dept.)

Engr. Prof. M.C Ndinechi
(Dean School of Electrical Sys. Eng. and Tech)

Date

Prof. Mrs. J. Nwosu
(Dean, Postgraduate School)

Date

External Examiner

Date

DEDICATION

This work is dedicated to the Nigeria Electricity Industry workers.

ACKNOWLEDGEMENTS

I remain grateful to the Lord Jesus Christ for whom I exist today. My appreciation goes to my supervisor, Engr. Prof. O.J Onojo for his down-to-earth approach to research and analyses. To the Head of Department, Electrical and Electronic engineering, Engr. Dr. N. Chukwuchekwa, I am grateful for her dogged approach in assisting me to achieve my academic dreams. I appreciate the Dean School of Electrical Systems Engineering and Technology, Engr. Prof. M.C Ndinechi, for his unparalleled support in this programme. I want to thank Prof. Mrs. J. Nwosu, the dean of Postgraduate School, whose office brings it all together. To my lecturers, Engr. Prof. D.O Dike, Engr. Prof, E.N.C Okafor, Engr. Prof. L.O Uzoechi and Engr. Dr. M. Olubiwe for giving us a good foundation during course work. To Engr. Mrs.N. Euka-Ejinefu and Engr. R. Enweliku for assisting me with the contacts and data of the Nigeria power system network. To my darling wife Amaka and my sons Chimdile and Miracle, the joy you radiate always makes motivates me to keep trucking. I am indebted to my parents Engr. and Mrs. E.O Ibuadinma for their support from cradle to date.

TABLE OF CONTENTS

Certification	i
Dedication	ii
Acknowledgements	iii
Abstract	iv
Table of Contents	v
Lists of Tables	viii
Lists of Figures	ix
CHAPTER ONE: INTRODUCTION	
1.1 Background	1
1.2 Statement of Problem	4
1.3 Objectives of study	5
1.4 Justification of study	5
1.5 Scope of study	5
CHAPTER TWO: LITERATURE REVIEW	
2.1 The Nigeria Power Grid	6
2.1.1 The Structure and Performance of Nigeria Electric Power Grid.	6
2.2 Photovoltaic Systems.	9
2.2.1 Off Grid Photovoltaic System	10
2.2.2 Grid Tied Photovoltaic System	10
2.3 Utility Scale Photovoltaic Systems.	11
2.4 Utility Scale Storage	12
2.5 Performance Analysis of Power System Networks.	13
2.5.1 Load Flow Analysis	13
2.5.2 Contingency Analysis	14
2.5.3 Cost Analysis	17
2.5.4 Levelized Cost of Electricity	17

2.6	Modelling and Simulation of Power System Networks.	19
2.7	Power System Analysis Software.	24
2.8	Power System Islanding.	28
2.9	Review of Related Works	30
CHAPTER THREE: MATERIALS AND METHODS		
3.1	Introduction	34
3.2	Material	34
3.2.2	Software Tools.	34
3.3	Methodology	36
3.3.1	Network Selection and Data Collection.	36
3.3.2	Procedure for the project.	36
3.3.3	Flow Chart	37
3.3.4	Data of Generation Stations.	38
3.3.5	Inter-Bus Transformers.	38
3.3.6	Loads	39
3.3.7	Transmission Lines	40
3.3.8	Single Line Diagrams of the Network	41
3.3.9	Load Flow Analysis.	42
3.3.10	PowerWorld Load Flow Simulation	44
3.3.11	Contingency Analysis	47
3.3.12	Contingency List	47
3.3.14	Levelized Cost of Energy calculation	47

CHAPTER FOUR: RESULTS AND DISCUSSION

4.2 Results from Load Flow Analysis of the Network without PV System	50
4.3 Results from Load Flow Analysis of the Network with PV System	52
4.4 Results from Contingency Analysis of the Network without PV System	52
4.5 Results from Contingency Analysis of the Network with PV System	56
4.6 Results from Contingency Analysis of the Network When there is Zero Insolation at the PV Power Stations	57
4.7 Results from Cost Analysis	59

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusion	60
5.2 Recommendations	61
5.3 Contribution to Knowledge	61

REFERENCES

APPENDIX

LIST OF TABLES

Table 2.1: Cost generating in Nigeria	17
Table 2.2: Parameters of GENROU model	26
Table 2.3: REG-C Input parameters	27
Table 3.1: Data collection template	35
Table 3.2: Generation station Voltage and power ratings	38
Table 3.3: Data of the inter-bus transformers	39
Table 3.4: Load Data	39
Table 3.5: Transmission Line Data	40
Table 3.6: Cost Components of the LCoE for CCGT and PV systems	48
Table 4.1: Results of the PowerWorld Load Flow Simulation	50
Table 4.2: Results of the Power World Load Flow Simulation with PV system	52
Table 4.3: Results of the Power World contingency analysis without PV system	54
Table 4.4: Results of the Power World contingency analysis without PV system	56
Table 4.6: Results of the Power World contingency analysis at zero insolation.	58

LIST OF FIGURES

Figure 2.2: Schematic Diagram of Off Grid PV System	10
Figure 2.3: π -model of a transmission line between nodes k and m	20
Figure 2.4: Model of a generator connected to bus k	21
Figure 2.5: Equivalent circuit of a PV cell	21
Figure 2.6: Equivalent circuit of a generalized PV generator	22
Figure 2.7: Model of a load connected to bus k	24
Figure 2.8: Block diagram of GENROU model	27
Figure 2.9: REG-C model block diagram	27
Figure 3.1: Flow chart for the procedure.	37
Figure 3.2: Single Line Diagram of the network	41
Figure 3.3: Single Line Diagram of the Modified Network.	42
Figure 3.4: Typical Power System Network	42
Figure 3.5: PowerWorld model of the network	45
Figure 3.6: PowerWorld Model of the Network with PV systems integrated	46
Figure 4.1: Bar chart of the Bus voltages without PV system	51
Figure 4.2: Bar chart of Voltage angles without PV system.	52
Figure 4.3: Bar chart of Bus Voltages with PV system	53
Figure 4.4: Bar chart of Voltage angles with PV system	54

ABSTRACT

This thesis focuses on the performance evaluation of 620MW photovoltaic (PV) systems integrated into an islanded Nigeria electric power grid. Electricity supply in Nigeria is abysmal and the effects on the economy and quality of life of Nigerians. To grow Nigeria GDP by 7%, additional generation capacity of 119,200MW is needed by 2030 while contributing mitigating of the effects of greenhouse gases, deploying renewable energy sources must be considered in generation planning. According to African-EU Renewable Energy Corporation Programme the installed capacity of off grid generation in Nigeria is about 14 GW, slightly above the grid capacity of about 10 GW. This work reviews various related literatures. It carries out load flow studies and Contingency analysis, using a set of possible contingency scenarios, of an islanded segment of the Nigeria Electric network namely Afam Power Substation to Yenogoa Transmission Substation without utility scale PV system integrated. The studies are done also with 500MW PV system integrated at Afam Power Station and 120MW at Gbarain Power Station. The data used were valid upto the year 2021. This work utilizes PowerWorld Simulator for these analyses. The results show a reasonable degree of stability was achieved when there was loss of generation. For example, with Afam Generation station open, system violations went from 14 (without PV) to 3 (with PV). Finally, the results for levelized cost of electricity (LCoE) for combined cycle gas turbines and PV systems show that the LCoE for PV systems was 0.1273 \$/kWh, which is still less than LCoE of 0.0970 \$/kWh The results also show that such hybrid generation planning can provide a high degree of redundancy in our fragile network.

Keywords: performance evaluation, contingency analysis, levelized cost of electricity, power system islanding, cost analysis

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The challenge of balancing electric power demand and supply in Nigeria has remained persistent and seemingly unresolved over the years. Several government and industry players have done a lot to improve the system, yet outcomes remain abysmal. In 2008, A.S Sambo showed that based on the so- called reference scenario, at 7% GDP growth, electricity demand projections for Nigeria are expected to peak at 119,200MW in the year 2030 (Sambo, 2008). With a base year of 2005, this would have implied a yearly addition of 4,538MW.

1.1.1 Off-Grid Generation

The term off-grid power generation can be seen as small-scale electricity generation to a single or limited number of customers. It is estimated the installed capacity of off grid generation in Nigeria is about 14 GW (African-EU Renewable Energy Corporation Programme, 2016). This capacity exceeds the overall installed capacity. Many manufacturing industries rely mostly on off grid generators for their electricity needs. The current off grid generation is fraught with inefficiencies as most of the systems are still running on fossil fuel products and are not effectively utilized. While off grid generation will assist Nigeria in achieving power system adequacy in Nigeria, it is fraught with challenges.

Most of the off-grid projects are awarded to score cheap political victory at elections by politicians and the ones that are completed are often done with poor quality. Off-grid projects awarded in Nigeria are not sustained because of the changes in government. Every new administration often comes in with its own fresh agenda to the detriment of existing and unfinished projects.

Again, the pervasive effects of substandard products in Nigeria are felt in power sector as well. There is hardly a link between the cost of off grid power equipment

and their quality. This has made off-grid projects fail in many cases in the country. Finally, the technology of off grid equipment produced in Nigeria are still at experimental stage. Their functions are often short-lived (Julius et al., 2014).

1.1.2 The Carbon Emission Issue

Climate change is one of the sole causes of adverse environmental conditions. In 2017, about 65% of electricity is produced from coal, natural gas and oil (World Nuclear Association, 2020). Renewable sources, hydro, wind, biomass, solar and geothermal power account for a quarter of the global electricity production (Faroosh, 2019). Finally, nuclear accounts for 8% of electricity production today as at 2017(International Atomic Energy Agency, 2018).

The electricity is produced by the combustion of fossil fuels to generate heat needed to power steam turbines. Carbon dioxide (CO₂) is produced by burning these fuels and is chiefly responsible for global warming (Abdallah & El-Shennawy, 2013). In Nigeria, electricity generation industries accounted for 8.5% share of CO₂ emission in 2014(Odewale et al., 2012).

1.1.3 Global trends and Kaya's Equation

The Paris Agreement attempts to bring UN member nations together to undertake the ambitious project of combating climate change. The Paris Agreement aims to mitigate the threat of climate change by keeping a global increase in temperature well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius (*The Paris Agreement* / UNFCCC, 2018).

A simple model to assess factors governing greenhouse gas emission was developed by a Japanese scientist Yoichi Kaya. He stated that the evolution of carbon emissions depends on 4 factors namely (Tavakoli, 2017);

- a. The increase in carbon content of the energy we consume (CO₂/ energy).
- b. The energy intensity of our economic activity (generally measured by the amount of energy consumed per unit of Gross Domestic Product (GDP)).
- c. The wealth per person (GDP / capita).

d. The growth of population (Lambert-Lalitte, 2019).

The equation is set as follows;

$$\text{Carbon emission} = (C_e/P_e) \times (P_e/\text{GDP}) \times (\text{GDP}/\text{Pop}) \times \text{Pop} \quad (1.1)$$

C_e = Carbon emission

P_e = Primary Energy Consumption

GDP= Gross domestic product

Pop = Population

From equation 1.1, the various variables that influence greenhouse gas (GHG) emissions are shown, therefore minimizing each of the variables will contribute to achieving the goal of the Paris Agreement.

According to United Nations report, the world population will reach 9.8 billion in 2050, an increase of 30% from the present 7.6 billion and this growth pattern is expected to continue to climb (UNDESA, 2017). In other words, world population will continue to rise and there is not much to be done to produce significant change that will impact on reducing carbon emission.

Considering the GDP per capita, the world economy is expected to double by 2050 due to continued increase in productivity offered by technological advancements (PricewaterhouseCoopers, 2017). Therefore, the only options left to be appropriated effectively in reducing carbon emission is reducing the primary energy consumption per GDP and moving towards including as many as possible renewable energy sources in our energy mix. The former can be achieved by developing more energy efficient technologies and carbon capture and storage systems.

1.1.4 The Cost Issue

Renewable energy resources have consistently shown a downward pattern when it comes to the issue of cost. According to the International Renewable Energy Agency (IRENA), the cost of renewable energy will continue falling so fast and will be consistently cheaper than the traditional fossil fuels for electricity generation within just a few years. It further stated that there has been a remarkable

fall in electricity costs from utility scale solar photovoltaic projects since 2010(International Renewable Energy Agency, 2018). There are several reasons for these sharp drops in cost, one being the constant advancement in renewable energy technologies. Secondly, the policy preference of government for harnessing renewable energy resources for power generation. Again, levelized cost studies conducted by Lazard, an international financial advisory and asset management firm shows that the mean levelized cost of energy of utility-scale PV technologies is down approximately 13% from 2017 and the mean levelized cost of energy of onshore wind has declined almost 7% (Lazard, 2018).

1.2 STATEMENT OF PROBLEM

The persistent imbalance between electric power demand and supply in Nigeria, driven by insufficient and inefficient power generation capacity, heavy reliance on fossil fuels, and poorly implemented off-grid systems, exacerbates carbon emissions and hinders sustainable economic growth. Despite global trends favoring renewable energy adoption and energy efficiency, Nigeria faces systemic challenges such as high costs, technological limitations, inadequate policy frameworks, and political interference, which prevent the effective integration of renewable energy sources and the achievement of power system adequacy.

The core issue lies in the obsolescence of Nigeria's transmission grid, which raises concerns about its capacity to integrate an increasing share of variable renewable energy sources. Therefore, a comprehensive performance analysis is essential to assess its readiness for this transition and ensure a stable and efficient power system.

1.3 OBJECTIVES OF STUDY

The primary objective of this project is to carry out a performance analysis of 620MW utility scale Photovoltaic Systems integrated into an islanded Nigeria Electric power grid.

The specific objectives include:

- a. To model the islanded Nigeria power network with a typical large-scale solar power plant integrated.
- b. To perform load flow analysis of the islanded network with the PV system integrated.
- c. To perform contingency analysis of the network with the PV system integrated.
- d. To perform levelized cost of energy calculation of the system.

1.4 JUSTIFICATION OF STUDY

While the issue of network capacity and capability of the transmission and distribution network are receiving huge attention in Nigeria, the generation planning, operation, security and expansion must be given adequate consideration. It has been shown that with average generation capacity of 4000 MW, Nigeria's per capita electricity consumption, at about 144 kWh, is significantly lower than the global average of 3,126 kWh (Ugochukwu K. Elinwa et al., 2021). Hence, this study is designed to determine the possibility of enhancing electricity generation using utility scale photovoltaic systems. This work intends to propose the addition to generation capacity using the environment friendly source-solar energy.

1.5 SCOPE OF STUDY

This research studies the performance of a representative model of the Nigeria power grid. The selected network to be used spans from Afam Generating Station to Alaoji TS BUS to Owerri TS BUS to Yenogoa TS. This comprises 12 buses. The systems operations analysis to be determined are Load flow analysis, contingency analysis and cost analysis.

CHAPTER TWO

LITERATURE REVIEW

Performance analysis of systems has been a well-established method of studying system behaviour under specified operating conditions. In getting along with the various analyses, it is pertinent to go through previous related literatures. This will enable us progress without reinventing the wheels while achieving the objectives of this work. This chapter intends to show that this research will contribute to enhancing power system operations in Nigeria and add to knowledge in the literature.

2.1 THE NIGERIA ELECTRIC POWER GRID

An electric power grid is an interconnected network used to deliver electricity from producers to consumers. It consists of generating stations, high voltage transmission lines and distribution lines that transfer power to customers. Nigeria currently operates a single electric power grid.

2.1.1 The Structure and Performance of Nigeria Electric Power Grid

The structure of the Nigeria power grid is basically divided into 3 segments namely;

- a. Generation.
- b. Transmission.
- c. Distribution.

A. Generation

Presently, there are currently twenty-eight (28) grid-connected gas and hydroelectric power generating companies (“GenCos”) in Nigeria (Nigerian Electricity Regulatory Commission, 2022). The total installed capacity is about 13,097MW as at December 2022 and available capacity varies around 4,059MW. Thermal based plants form 81% of the generation pool. This subsector comprises

of the privatized GenCos, Independent Power Producers (IPPs) (Nigerian Electricity Regulatory Commission, 2022).

B. Transmission

Transmission Company of Nigeria (TCN) manages the electricity transmission network in the country. TCN was on July 1st, 2006 issued a Transmission License with the responsibilities of wheeling power at high Voltage, operate the National Grid and Market Operation Service. The transmission system in Nigeria comprises 330 kV and 132 kV circuits and substations. TCN operates 10 regions at Lagos, Oshogbo, Kaduna, Bauchi, Shiroro, Enugu, Port Harcourt, Benin, a National Control Centre at Oshogbo and 3 Regional Control Centers at Lagos, Benin, Kano and a supplemental Control Centre at Shiroro (Transmission Company of Nigeria, 2019). The major functions include;

- i. Provision of Transmission Services
- ii. System Operation Services.
- iii. Market Operation Services (Nigerian Electricity Regulatory Commission, 2022).

The Transmission Service Provider (TSP) is saddled with the role of development and maintenance of the transmission infrastructure.

The System Operator (SO) manages the flow of electricity throughout the power system from generation to distribution companies. The SO ensures that the grid lines are reliable. It is actively involved in planning, dispatch, and control of the electricity on the grid (Nigeria Electricity System Operator, 2019).

The Market Operator (MO) enforces the market rules of the Nigerian Electricity Supply Industry (NESI). It is responsible for the administration of the Electricity Market and promoting efficiency in the market.

C. Distribution

There are 12 electricity distribution companies (Discos) in Nigeria. The Distribution companies operate and manage the 33kV, 11kV and 0.415kV networks. They are in direct contact with power consumers. Distribution network are basically of two types: radial network and interconnected network. In a radial network, the feeder leaves the station and passes through the network area with no normal connection to any other supply. While an interconnected network has multiple connections to other points of supply.

In Primary Distribution System, there is high voltage (11 and 33kV) networks fanning out from substations. In most cases, large industries consumers are often encouraged to take supply at primary distribution system (Chinwuko et al., 2011).

In 2013, with the conclusion of the privatization process, expectations of citizens were raised that there will be an improvement in the power sector. It is expected that the Distribution companies who are the frontline service providers will ultimately rise up to the challenge of delivering on the promises. However, the performance so far has been abysmal. Some of the issues are,

- i. The Labour issue: The issue of paying compensation and severance allowances to members of staff of the defunct Power Holding Company of Nigeria .
- ii. Grid energy insufficiency and instability.
- iii. Network infrastructure challenges (overloaded transformers and feeders, obsolete equipment, limited network, lack of automation, etc.).
- iv. Tariff challenges and revenue shortfalls (non-cost reflective tariffs, low collection efficiency, etc.).
- v. Metering challenges (huge metering gap, estimated billing, poor meter maintenance, etc.).
- vi. Operational challenges (long feeders, quality of workforce, large operational areas, etc.).

- i. Energy theft.
- ii. Funding challenges (absence of long term “patient” capital (equity/debt) to fund capex investment, high cost of borrowing, poor credit history of Discos, etc.) (Omonfoman, 2016).

Nigeria electric power grid performance is below average. The average daily power generation is about 4,000 MW. K. Okakwu stated that due to the inadequacy of the transmission network capacity, the power system could be stressed to such an extent that relatively small disturbance can cause a great upset which may eventually result in a possible voltage collapse (Kema Okakwu, 2017). Generally, system collapse may arise due to any of the following reasons; radial grid system, weak system inertia, faulty protection system, defective governor, vandalization, natural accident, poor maintenance, human error, corruption, neglect of government by politicizing the sector and lack of adequate investment (Uche et al., 2018).

Nigeria has recorded a total of 21 total system collapse between 2022-2024 (Energy Central News, 2024). The Nigeria National Grid is highly venerable to voltage instability. It was observed that the high rate of system collapse is largely due to faults (technical challenges) on the network, the state of the power system equipment and to some extent political issues (Samuel et al., 2014).

2.2 PHOTOVOLTAIC SYSTEMS

A photovoltaic (PV) system is a system made up of one or more solar panels combined with an inverter and other electrical and mechanical hardware that use energy from the sun to generate electricity (Donev et al., 2024). Photovoltaic systems can be operated in off-grid PV or grid tied modes.

2.2.1 Off-Grid Photovoltaic System

Off-grid solar PV system is independent of the grid and provides freedom from power quality issues and electricity billing. The excess energy can be accumulated in the battery storage units through superior control (Karthikeyan et al., 2017).

The structure of an off-grid PV system is shown in figure 2.1, with bus configurations and representative interconnections between components. This figure describes the arrangement of the different solar energy components based on voltage types.

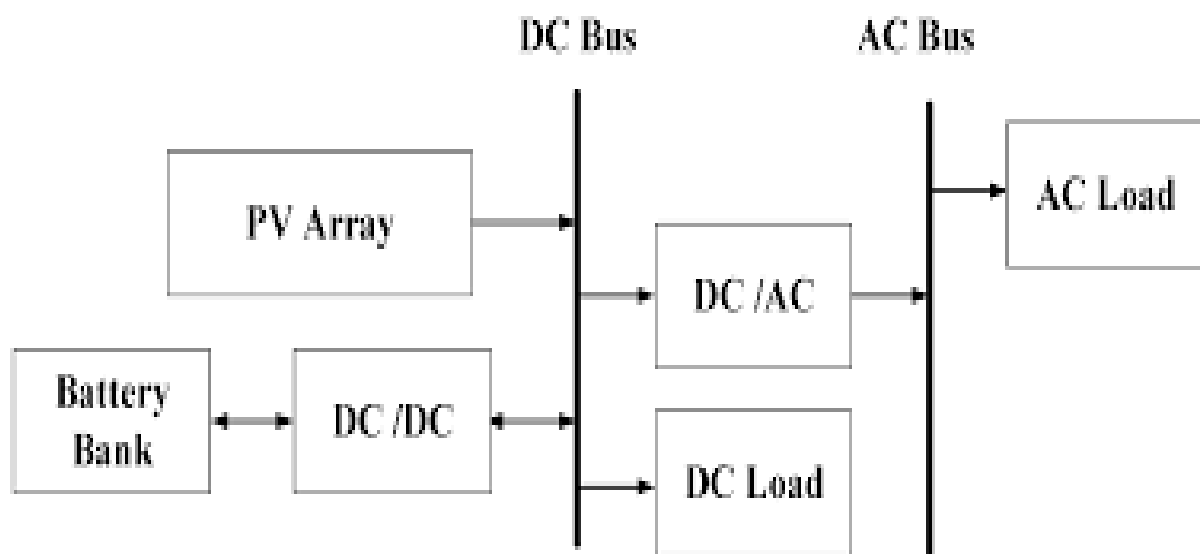


Figure 2.1: Schematic Diagram of Off Grid PV System (Madziga et al., 2018).

Off-grid Photovoltaic systems are basically small power plants designed to provide electricity from a centralized solar photovoltaic power plant to a small locality like village or a building (The World Bank Group, 2006).

2.2.2 Grid Tied Photovoltaic System

In grid-tied systems, the DC electricity produced by the PV array is fed into the grid inverter. The inverter converts DC electricity into AC. This AC is supplied to the grid. They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Grid-connected PV systems usually inject active power energy to the grid. They are mainly used to avoid the dependence of

fossil fuels (Karthikeyan et al., 2017). The integration of photovoltaic systems into the grid is gaining more traction today as a very important application of PV systems. This comes with inherent challenges as this variable and intermittent energy source constitutes a significant part of the total system generation.

2.3 UTILITY SCALE PHOTOVOLTAIC SYSTEM

Utility scale solar power plants are energy generating facilities capable of producing large amounts of electricity that can be fed into the electricity transmission grid; they range in size from 10 MW to over 200 MW (Xoubi, 2015). Utility-scale solar electricity now costs less than conventional generation in many markets attributed to reduced costs of modules & improvement in efficiency, innovations in PV technologies and improved investment climate. Today there are several large-scale photovoltaic plants with grid integration. We have some existing utility-scale PV plants.

In India, there is Kurnool Ultra Mega-Solar Park (KUMSP), this is a solar electric power plant in Panyam Mandal of Kurnool District, Andhra Pradesh in India. It has about 4,000,000 solar panels of 315 watts each connected to the nearby four 220/33 kV pooling stations of 250 MW each and a 400 / 220kV grid substation. The facility currently produces 90% of its installed capacity (V.Raghavendra, 2017). Again, Topaz Solar Farms this is located on 4,700 acres of land in San Luis Obispo County, California. It is 550-megawatt photovoltaic plant. The site is adjacent to the existing 230-kV Morro Bay-to-Midway transmission line, which provides access to transmission capacity (BHE RENEWABLES, 2019).

There is also Solar Star, U.S, a 579 MW Solar power project in the Antelope Valley was developed by Sunpower and commissioned in June 2015. The project uses 1.7 million Sunpower monocrystalline silicon modules on spread over 3,200 acres. It produced an average of 1,534 GWh of electricity annually between 2015 and 2016(Buckley & Shah, 2018).

The Agua Caliente Solar Project is a plant located 65 miles east of the city of Yuma, Arizona. It is a 290MW AC PV solar plant. It is designed to be connected to a 500kV transmission line (First Solar, 2018).

2.4 THE UTILITY SCALE STORAGE

The challenge of oversupply of energy when the sun shines and wind blow and the shortage when the wind stops and the sun sets can be overcome by the so called “big battery technology”. Although in infancy, the utility scale battery technology helps in taking care of the imbalances between supply and demand. Typically, utility-scale battery storage systems have a storage capacity ranging from around a few megawatt-hours (MWh) to hundreds of MWh. Utility Scale battery storage systems can provide grid services such as frequency response, regulation reserves and ramp rate control (IRENA, 2019).

Utility scale batteries can provide the following services namely;

- a. **Arbitrage:** This involves charging the battery when energy prices are low and discharging during more expensive peak hours. That is the system enables buying electricity when the tariff is low and using that electricity during peak periods when the tariff rates are at their highest.
- b. **Firming Capacity:** With the fluctuations in renewable energy generation system due to variability of the sources, utility scale batteries can be used to cushion these effects. Firm capacity describes the amount of installed capacity that can be relied upon to meet demand during peak periods or other high-risk periods (Bowen et al., 2018).
- c. **Black Starting:** Large generators, when starting, need an external source of electricity to perform key functions before they can begin generating electricity for the grid. Utility scale storage comes in handy.
- d. **Frequency Regulation:** Grid frequency dip can occur in power systems when there is an imbalance between the power supply and the power demand and this can go beyond the specified limits. Utility-scale battery storage systems can

be used for frequency regulation. Utility scale battery storage systems can typically respond to such requirements within milliseconds unlike its conventional generator counterpart (IRENA, 2019).

2.5 PERFORMANCE ANALYSIS OF POWER SYSTEM NETWORKS

Continuous performance analysis of power system networks is required in the monitoring and control of electricity networks. Events like increased power demand, which involves line expansions hence more power transfer in the system, will require system operators to carry out certain analysis. This process helps in economic justification of investments, grants insight into the technical performance of the system with respect to expected and unexpected events (Kudal et al., 2017).

2.5.1 Load Flow Analysis

Under steady state conditions, the system is seen to be performing within the set operating points. Various system variables lie within the expected limits. A typical power system network can contain several branches and nodes. Equations can be formulated in node-admittance form with node currents as variables. With the currents known the nodal voltages can be evaluated. Since, power is often known in power system, the equations in terms of power at the buses are often evaluated. This is known as Power Flow Equations, while the analysis is also known as Load Flow Studies (Saadat, 1999).

They are necessary for planning, operation, economic scheduling, transient stability, contingency studies and control of an existing system as well as planning its future expansion. The power flow solution is used to evaluate the bus voltage, branch current, real power flow and reactive power flow for the specified generation and load conditions (Onojo et al., 2013).

2.5.2 Contingency Analysis

Contingencies are disturbances capable of deviating power system networks from normal operations. This could be sudden loss of generation, loss of load, sudden increase in load, transmission line failure, equipment failure etc. In contingency analysis, operator seeks to know what might happen to the system when unplanned events occur. It essentially offers answers to questions such as “What will be the state of the system if an outage on part of the major transmission system takes place?” (E El-Hawary, 2000). It is further defined as the study of the outage of elements such as transmission lines, transformers and generators, and investigation of the resulting effects on line power flows and bus voltages of the remaining system (Onojo et al., 2015) .

To carry out Contingency Analysis of any network, first the detailed electrical model of the power is developed. This is the real-world equipment and connections of a power system (typically a one-line diagram) translated into a mathematical model of the power network that is suitable for solution by computer algorithms. This network model like the electrical characteristics of the equipment (such as the impedance of transmission lines). With the power network model initialized, a series of contingency events called contingency list that is prepared by the operator is executed. A "power flow" analysis for each potential problem that is defined on a contingency list is conducted. A "network solution" consists of these calculated results (voltages, real, reactive power etc) for every bus and branch in the power network model.

Contingency analysis can be viewed from two perspectives, namely Primary Contingency (N-1) Analysis, a single contingency condition, where there loss of only one part of the network say transmission equipment tripped but without including the bus bar and radial line and Multiple/Secondary (N-1-1) contingency in which case series of unplanned events occurs(Ramanaiah & Rao, 2014). There are various methods of contingency analysis which include the following:

a. AC Load flow method.

AC load flow is used to study system behavior with respect to parameters like voltage, angle, active and reactive power flows at the buses and lines. Thus, AC load flow method reveals the system overloads and voltage bounds violation accurately, when a contingency scenario occurs. Its major setback is long computation time as the systems to be analyzed gets larger. Where there is conflict between accuracy and speed and accuracy is preferred, it is recommended to use AC load flow method.

b. DC Load flow method.

Direct current (DC) power flow is a common model for power system contingency analysis its computation time is shorter. It reveals only real power flow in the system network branches. The shorter computational time of DC load flow is due to the impact of linearization of power flow solution. The following assumptions are made;

- i) Voltage angle difference between two buses is considerably small so that its approximate sine is equal to that angle and its cosine is one.
- ii) All voltage magnitudes are approximately equated to be 1.00 p.u.
- iii) The system is an ideal network. i.e. lossless network branches.
- iv). The tap settings are ignored.

The advantages DC load flow over the full AC load flow under Newton Raphson method are,

- i) The system impedance matrix is less about half the size of the full problem.
- ii) The problem is simplified to be non-iterative, just requiring a simple calculation in order to have final solution.
- iv) Impedance matrix is independent to the system network; hence it is calculated once throughout the whole calculation to have a final solution.

c. Z-Matrix method.

In this method, the bus impedance matrix associated with the system under consideration and the system modified by either line removals or additions. The Z-matrix of a system is now obtained by inverting the bus admittance matrix. In Z-matrix method, we inject fictitious current into the buses linked to the element to be removed based on our contingency list, the current is selected such that the value is equal to the base case flow. All other bus currents are set to be equal to zero. In effect, this procedure creates throughout the system a current flow pattern that will change in the same manner as the current flow pattern in the AC load flow solution when the element in question is removed. This method is more accurate compared to DC load flow method and the results are comparable to those obtained using AC power flow (Sureban., 2019). The Z-matrix further describes the relationship between the bus voltages and current injections by,

$$[V_{bus}] = [Z_{matrix}] [I_{bus}] \quad (2.1)$$

Where $[V_{Bus}]$ and $[I_{Bus}]$ are the vectors of bus voltages and bus current injections, respectively. $[Z_{Matrix}]$ is the bus impedance matrix. The algorithm for building the Z-matrix transmission lines one by one and divides them into four types,

- (i) Adding a line from a new bus to the reference bus.
- (ii) Adding a line from a new bus to an existing bus.
- (iii) Adding a line from an existing bus to the reference bus.
- (iv) Adding a line between two existing buses (Teng et al., 2004).

d. Performance index method.

In this method, the contingencies are selected by calculating some indices used to measure severity. These indices are known as Performance Indices (PI). They can be calculated using the basic load flow algorithms. The contingency with the highest value of PI is ranked first. The analysis is then done starting from the contingency that is ranked one and is continued till no severe contingencies are found. The two kind of performance index normally used are

- i. Power performance index (PI_P) which shows the violation of line active power flow.
- ii. Reactive power performance index (PI_V) corresponds to bus voltage magnitude violations.

2.5.3 Cost Analysis

The cost generating electricity with the existing technologies in Nigeria is shown in Table 2.1.

Table 2.1 depicts the various components of cost for gas-based and Hydro-based power plants are evaluated based on the efficiency of the technology used, investment cost, fuel cost etc.

Fuel Resource	Eff. %	CO ₂ (TC) per MWh	Investment Cost (₦ MWh)	Fuel Cost (₦ /MWh)	O&M Costs (₦ /MWh)	LCOE
Gas (Single Cycle)	57	0.23	1748.285	6096.25	608.7584	8453.293
Hydro	55	0	3334.09	0	1917.264	5251.354

Table 2.1: Cost generating electricity in Nigeria (Emodi & Yusuf, 2015).

To compare cost in electricity sector, capital cost and the Levelized cost of electricity are the basic parameters used. The Levelized Cost of Electricity is a lifecycle cost analysis of a power plant that uses assumptions about the future value of money to convert all future costs and revenues into current prices. Capital cost represents the amount that must be found at the outset to finance a power plant (Paul Breeze, 2010).

2.5.4 Levelized Cost of Electricity

Levelized cost of electricity (LCOE) is the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle. The key parameters required in calculating LCOE are capital costs, fuel costs, fixed and variable

operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type (U.S. EIA, 2019).

LCoE can be calculated using Equation 2.1.

$$LCoE = \frac{(\text{Capital Cost} * CRF * (1-T * D_{pv})) * \frac{F_{om}}{(8760 * \text{Capacity Factor})}}{(8760 * \text{Capacity Factor} (1-T))} + V_{om} + (F_p * H_r) \quad (2.2)$$

CRF = capital recovery factor, turning capital costs into annual values (if capital is financed at discount rate D)

F_{om} = Fixed Operation and maintenance Costs.

V_{om} = Variable Operation and maintenance Costs.

F_p = Fuel Price

H_r = Heat Rate

T = Tax rate

D_{pv} = Depreciation Factor

$$CRF = \frac{D * [(1+D)]^N}{[(1+D)]^N - 1} \quad (2.3)$$

D = Discount rate

N = Lifetime of System.

I_t = Investment expenditures in year t (including financing).

M_t = Operations and maintenance expenditures in year t.

F_t = Fuel expenditures in year t.

E_t = Electricity generation in year t.

r = Discount rate.

n = Life of the system (Foster et al., 2014).

Several models however exist for the calculation of LCoE. They include

i. California Energy Commission Cost of Generation Model (2012).

California Energy Commission LCOE assumes calculation of annual costs of generation for each technology (Ct) with further transformation of annual costs into the present value (sum of discounted annual costs). CEC model allows for calculation of LCOE for the plants types different in ownership: merchant owners, IOUs, or POUs with associated differences in financing. The U.S. NREL's Simple Levelized Cost of Energy LCOE is utilized for Nigeria (Roche, 2017).

ii. Bureau of Resources and Energy Economics (BREE) Australia Energy Technology Assessment (AETA) model. This model was developed specifically for Australian conditions and provides cost estimates for 40 electricity generation technology types.

2.6 MODELLING OF POWER SYSTEM NETWORKS

The components of power systems network can be defined by mathematical and graphical models.

2.6.1 Transmission Lines

The transmission line can be characterized by shunt and series parameters. They are,

R' = series resistance/km per phase (/km)

X' = series reactance/km per phase (/km) for series parameters and

B' = shunt susceptance/km per phase (Siemens/km)

G' = shunt conductance/km per phase (Siemens/km) for the shunt parameters.

Figure 2.2 is π - model of transmission line showing the line flows with associated impedances and admittances.

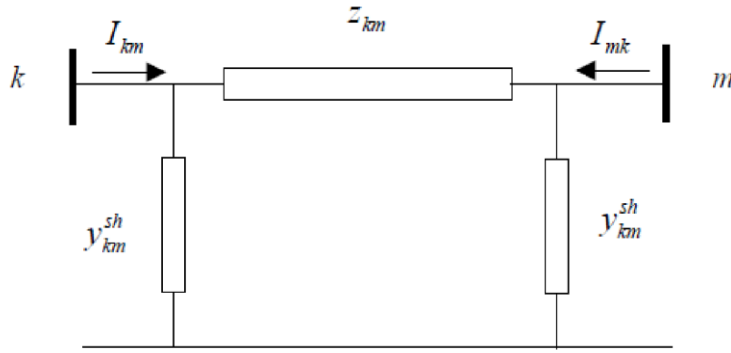


Figure 2.2: π -model of a transmission line between nodes k and m.

$$Z_{km} = R_{km} + jX_{km} = \text{series impedance} \quad (2.3)$$

Where, Z_{km} = Impedance between buses k and m.

I_{km} = Current from bus k to bus m.

y_{km}^{sh} = shunt admittance.

$$Y_{km}^{sh} = G_{km}^{sh} + jB_{km}^{sh} = \text{shunt admittance (Andersson, 2008)}. \quad (2.4)$$

2.6.2 Generator Model

In load flow analysis, generators are represented as current injections. Under steady state operation, generators are commonly controlled so that the active power injected into the bus and the voltage at the generator terminals are kept constant. Active power from the generator is determined by the turbine control and must of course be within the capability of the turbine- generator system. Voltage is primarily determined by the reactive power. The reactive capability of a generator depends on a number of quantities, such as active power, bus voltage and other operating conditions.

In Figure 2.3, a simplified model of the generator is shown with the current flow direction excluding the impedances. I_k^{gen} is the current flowing from the generator to the bus.

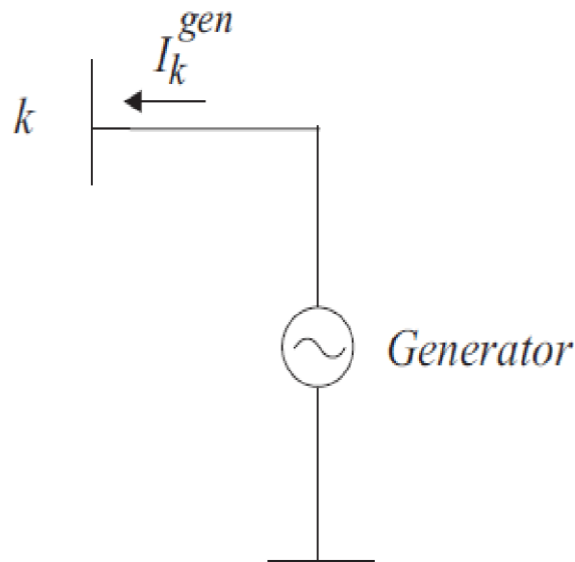


Figure 2.3: Model of a generator connected to bus k.

2.6.3 PV Generator Model

The solar cell is building block of the PV generator is, which is basically a P-N semiconductor junction that directly converts solar radiation into DC current using the photovoltaic effect.

The circuit model for a photocell is shown in Figure 2.4 with the associated arrangement of the single solar cell.

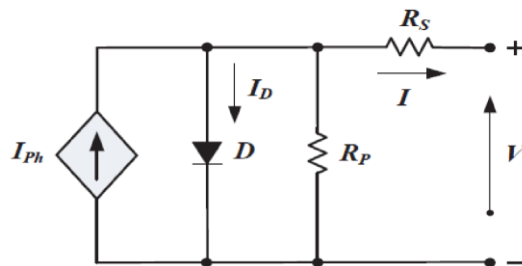


Figure 2.4: Equivalent circuit of a PV cell. (Molina, 2016)

Where,

I_{ph} = photocurrent.

I_D = diode current.

D = diode.

R_s = Series resistance.

R_p = Shunt Resistance.

In Figure 2.5 the equivalent circuit for the solar cells arranged in N_P -parallel and N_S -series is seen with the multiple configurations of solar cells.

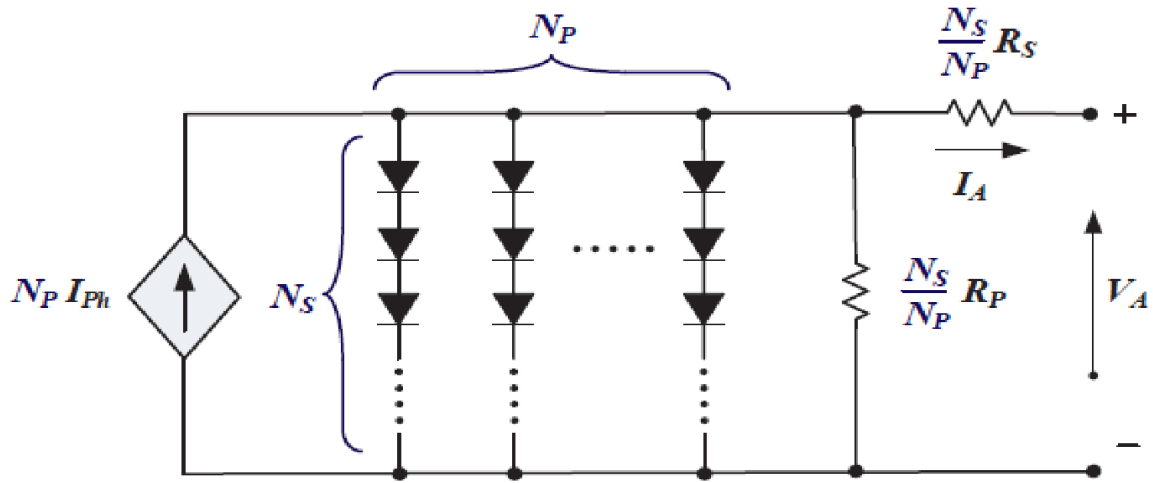


Figure 2.5: Equivalent circuit of a generalized PV generator. (Molina, 2016)

The mathematical model that predicts the power production of the PV generator, is a current-voltage relationship given by,

$$I_A = N_p I_{ph} - N_p I_{RS} \left\{ \exp \left[\frac{1}{A V_{Th}} \left(\frac{V_A}{N_s} + \frac{I_A R_S}{N_p} \right) \right] - 1 \right\} - \frac{N_p}{R_p} \left(\frac{V_A}{N_s} + \frac{I_A R_S}{N_p} \right). \quad (2.5)$$

From eqn (2.5) the definitions of the parameters are clearly stated

I_A : PV array output current, in A

V_A : PV array output voltage, in V

I_{ph} : Solar cell photocurrent, in A

I_{RS} : Solar cell diode reverse saturation current (aka dark current), in A

A: Solar cell diode P-N junction ideality factor, between 1 and 5 (dimensionless)

R_S : Cell intrinsic series resistance, in Ω

R_P : Cell intrinsic shunt or parallel resistance, in Ω

V_{Th} : Cell thermal voltage, in V, determined as $V_{Th} = k T_C / q$

k: Boltzmann's constant, 1.380658×10^{-23} J/K

T_C : Solar cell absolute operating temperature, in K

q: Electron charge, $1.60217733 \times 10^{-19}$ Cb. This nonlinear equation can be solved using the Newton Raphson iterative method. The parameters I_{ph} , I_{RS} , R_S , R_P , and A are commonly referred to as “the five parameters” from which the term “five-

parameter model” originates. To determine the current and voltage characteristic, these five parameters must be known. Therefore, the power generation of the PV generator for different operating conditions. Thus, in order to obtain a complete model for the electrical performance of the PV generator over all solar radiation and temperature conditions, Eq. (2.5) is supplemented with equations that define how each of the five parameters changes with solar radiation and/or cell temperature (Molina, 2016).

2.6.4 The Load Model

The load is often fed into the power network at a lower voltage level. Often the voltage in the distribution systems is kept constant by controlling the tap-positions of the distribution transformers which means that power, active and reactive, in most cases can be regarded as independent of the voltage on the high voltage side. This means that the complex power is independent of voltage.

The load current in complex form is

$$I_k^{\text{load}} = I_k^{\text{load}}(U_k) \quad (2.6)$$

Where $I_k^{\text{load}}(.)$ describes the characteristics of the load. The active and reactive power are given by Equations 2.7 and 2.8 as shown in Figure 2.7

$$P_k^{\text{load}} = P_k^{\text{load}}(U_k) \quad (2.7)$$

$$Q_k^{\text{load}} = Q_k^{\text{load}}(U_k) \quad (2.8)$$

In Figure 2.6, the load model, with the flow direction is depicted, however from this model the load characteristics are not shown.

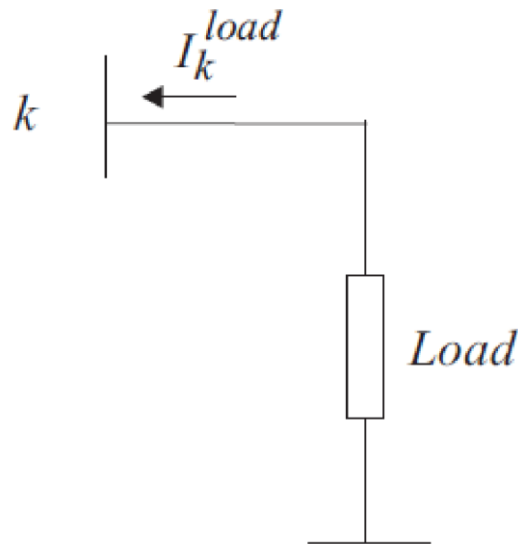


Figure 2.6: Model of a load connected to bus k.

2.7 POWER SYSTEM ANALYSIS SOFTWARE

Several software tools are available for the analysis and operations of power system networks. A few are discussed here.

A. ETAP: This is an electrical power system analysis and operation software. It finds use in modelling and visualization of electrical diagrams, analysis and optimization of power networks, analysis of protective devices, cable sizing, transient stability analysis etc (ETAP, 2019).

B. PowerWorld: It is a User-friendly and highly interactive power system analysis and visualization platform. Integrates many commonly performed power system tasks—Contingency Analysis, Time-Step Simulation, OPF, ATC, PVQV, Fault Analysis, SCOPF, Sensitivity Analysis, Loss Analysis, Transient Stability, etc (PowerWorld Corporation, 2019). PowerWorld is shown because of the flexibility it provides in the analysis of power system mainly at transmission voltage levels. It offers the functionality for implementing oneline diagrams of systems up to 250,000 buses. PowerWorld includes models that represents the parameters of various types of generators. Model includes power and voltage control parameters (MW Output, Min. MW Output, Max. MW Output, Mvar Output, Min. Mvar Output, Max. Mvar Output), as well as stability parameters

(Machine Model, Exciter Model, Governor Model, etc.) (Vulin et al., 2011). For example, the GENROU, GENSAL, GENTPF, and GENTPJ models represent round rotor and salient pole synchronous machines. The predominant difference between the GENROU/GENSAL and GENTPF/GENTPJ models is how they account for saturation.

- The GENSAL model uses simplifying approximations that significantly compromise treatment of magnetic saturation. The GENSAL model ignores saturation on the q-axis completely. In both the GENROU and GENSAL models, saturation is a single additive term.
- The GENTPJ and GENTPF models use approximations in their treatments of saturation but are more accurate than GENSAL and GENROU.

The GENROU model is shown in Figure 2.7, however, the processes are reflected with the various control blocks.

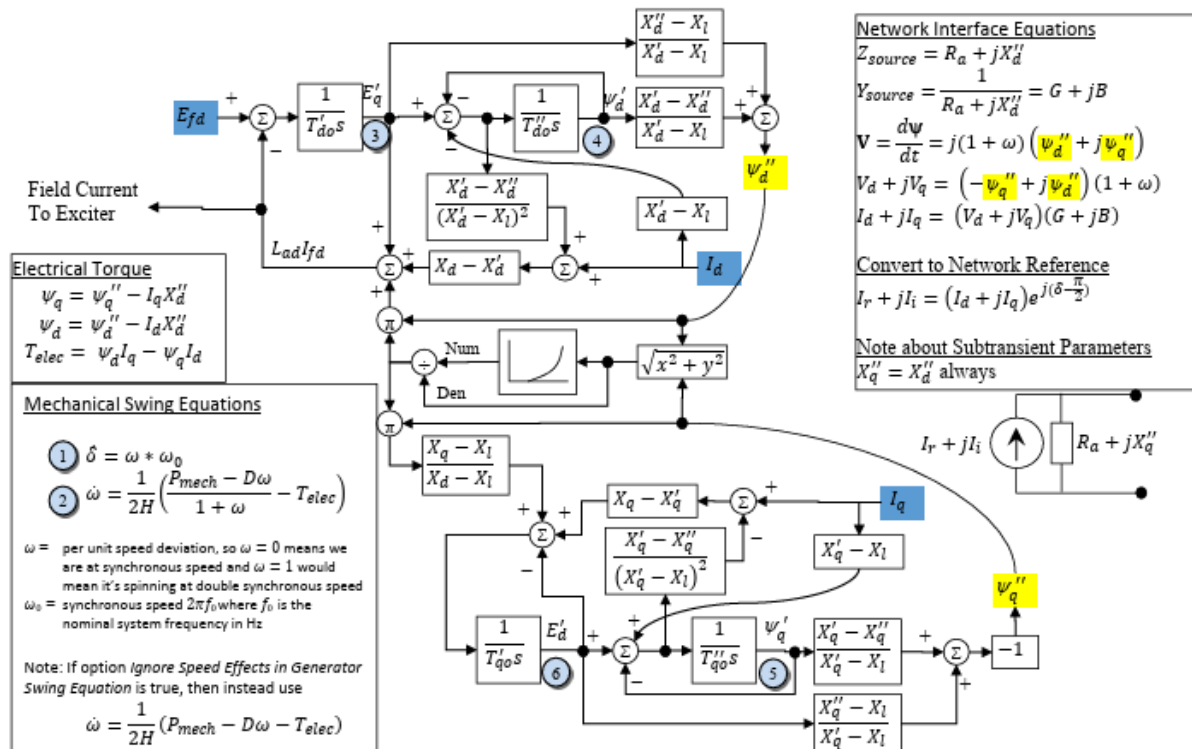


Figure 2.7: Block diagram of GENROU model (PowerWorld Corporation, 2020).

Table 2.2: Parameters of GENROU model (PowerWorld Corporation, 2020).

PARAMETER	DESCRIPTION
H	Inertia Constant sec
D	Damping Factor pu
Ra	Stator Resistance pu
Xd	D-axis Synchronous Reactance
Xq	Q-axis Synchronous Reactance
Xdp	D-axis Transient Reactance
Xqp	Q-axis Transient Reactance
Xdpp=Xqpp	Subtransient Reactance
Xl	Stator Leakage Reactance pu
Tdop	D-axis transient rotor time constant
Tqop	Q-axis transient rotor time constant
Tdopp	D-axis subtransient rotor time constant
Tqopp	Q-axis subtransient rotor time constant
S (1.0)	Saturation Factor at 1 pu Flux
S (1.2)	Saturation Factor at 1.2 pu Flux
Rcomp	Compounding Resistance for voltage control pu
Xcomp	Compounding Reactance for voltage control pu

For modelling renewable energy sources like solar energy, the PowerWorld Simulator model used is REG-C which is Renewable Energy Generator-Converter.

The “generator” model (REGC_A) to provide current injections into the network solution.

In Figure 2.8, the block diagram of a typical REG-C_A model and its input parameters for PV system are shown.

Here the various blocks and their processes are depicted.

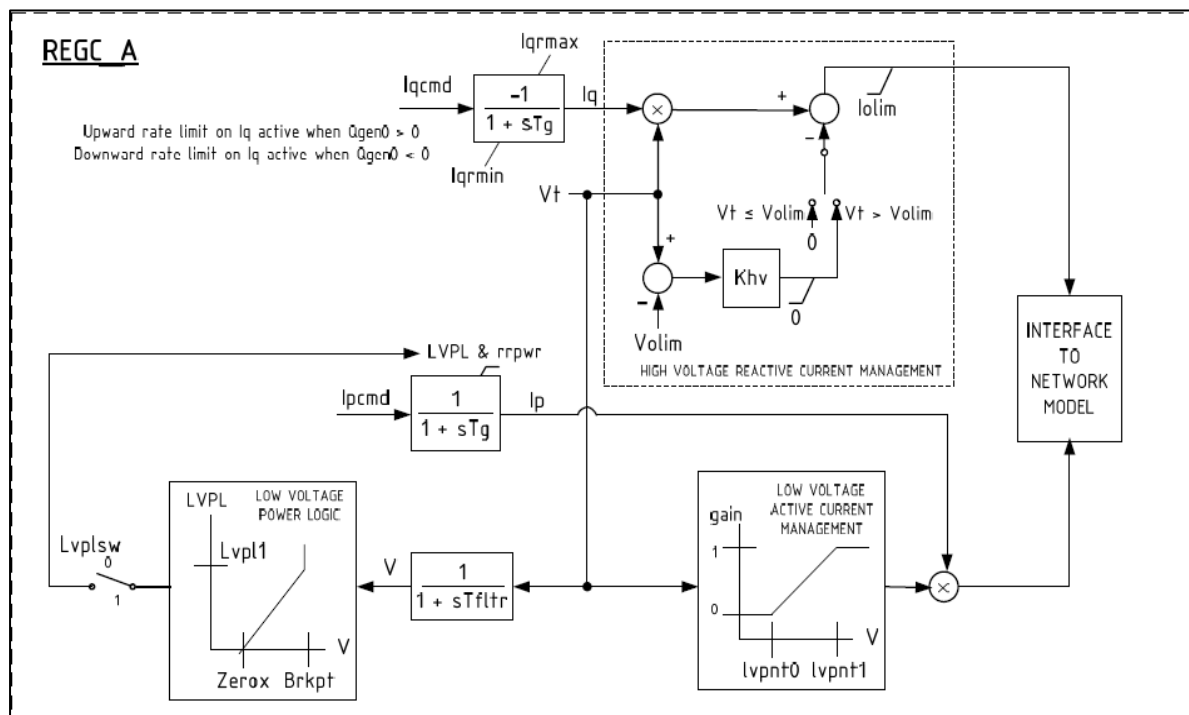


Figure 2.8: REG-C A model block diagram (PowerWorld Corporation, 2020).

Furthermore, the various parameters used in the model are described in table 2.3, for example the voltage limit for high voltage clamp logic is denoted by V_{olim} .

Table 2.3: REG-C Input parameters (PowerWorld Corporation, 2020)

PARAMETER	DESCRIPTION
Tfltr	Terminal Voltage Filter (LVPL) time constant (s)
Lvpll	LVPL gain breakpoint (pu current on mbase/pu voltage)
Zerox	LVPL zero crossing (pu voltage)
Brkpt	LVPL breakpoint (pu voltage)
Lvplsw	Enable (1) or disable low voltage power logic
Rrpwr	Active current up-ramp rate limit on voltage recovery (pu/s)
Tg	Inverter current regulator lag time constant (s)
Volim	Voltage limit for high voltage clamp logic (pu)
Iolim	Current limit for high voltage clamp logic (pu)

Khv	High voltage clamp logic acceleration factor
Lvpnt0	Low voltage active current management breakpoint (pu)
Lvpnt1	Low voltage active current management breakpoint (pu)
Iqrmax	Maximum rate-of-change of reactive current (pu/s)
Iqrmin	Minimum rate-of-change of reactive current (pu/s)

C. NEPLAN: A broad-based software that offers diverse solution in electricity sector, gas/heating/water supply, asset management etc. It covers all aspects of the electrical industry example transmission, distribution, generation/industrial networks and well suited for renewable energy system and smart grid applications (NEPLAN, 2019). It can be used to develop electrical models like a network combination of high-, medium- and low voltage networks, models for steady state and dynamic network behavior, renewables etc. (ABB, 2017).

D. Power System Analysis Toolbox (PSAT): PSAT is an open-source power system analysis toolbox for Matlab and GNU/Octave developed by Dr. Federico Milano and it can be used for power system analysis and control learning, education and research (Federic Milano, n.d.). PSAT can perform several power system analyses which include, continuation Power Flow (CPF), Optimal Power Flow, Small Signal Stability Analysis, Time Domain Simulations (Federico Milano, 2006).

2.8 POWER SYSTEM ISLANDING.

Islanding refers to the condition in which a portion of the grid becomes temporarily isolated from the main grid but remains energized by its own distributed generation resource(s). Islanding may occur accidentally or deliberately. Traditionally, islanding has been seen by utilities as an undesirable condition due to concerns about safety, equipment protection, and system control (Greacen et al., 2013). Islanding operation can be intentional may be desired in cases where the central grid is prone to reliability problems. This reflects the

Nigeria electric power scenario. Here, a segment of the grid is permitted to operate autonomously and provide service to local customers when the main grid is out. Transitioning between islanded and grid modes, protective devices are configured automatically. Interconnection of the islanded grid comes with some challenges technical namely,

- a. Frequency regulation.
- b. Voltage regulation.
- c. Disconnection and reconnection protocols in the event of grid disturbances.
 - a. Safe intentional islanding operation.
 - b. Control of faults when in grid-connected mode.
 - c. harmonization of technical standards among and within countries
 - d. Protection coordination

To implement intentional islanding, the system must perform these steps correctly,

- i. The system to be islanded must recognize an abnormal condition on the utility grid and disconnect a circuit breaker located at an appropriate location to separate mini grid load from the main grid.
- ii. Upon disconnecting, the islanded system must immediately switch from grid mode to autonomous mode. This will involve several operations depending on the type of systems. For example, automatic voltage regulator (AVR) controls may need to switch over immediately to operate in a different mode. The settings of various protective relays will likely need to be different in islanded mode, or separate relays employed.
- iii. The system must continue to sense line voltage on the main grid, and when main grid power returns to stable conditions, initiate reconnection, and return to control regimes (Greacen et al., 2013).

2.9 REVIEW OF RELATED WORKS

Insight into the behaviour of the Nigeria 330kV electric power grid under certain contingencies was discussed in “Contingency Analysis of the Nigeria 330kV Post-Reform Integrated Power System Using Power World Simulator” (Onojo et al., 2015). It was shown that Nigeria 330kV grid system is more complex and difficult to analyze, there are fewer violations in the system during contingencies when compared to previous works done on the pre-reform grid. The research further noted that even though parameter changes were always noticed at lines and buses during contingencies, most severe violations were noted in areas with single circuit transmission line between the buses. With these observations, direct corrective actions can always be planned for the system.

The paper “Improving Electricity Access in Nigeria: Obstacles and the Way Forward” showed that the obstacles to electricity access include; low efficiency and performance, security of fuel source for power generation, data inadequacy, regulatory barriers, lack of institutional arrangement, poor grid structure, dilapidated transmission and distribution network, low financial investment, lack of policy and project continuity.(Emodi & Yusuf, 2015) The research suggested encouraging investors to invest in renewable energy technology for the off-grid supply.

Mario Mureddu et al (2016), “Islanding the power grid on the transmission level: less connections for more security” studied the effect of islanding on the transmission grid and how it can enhance energy security and grid resilience. (Mario Mureddu et al., 2016) It was further shown that if the power grid gets fragmented under an outage, many of the resulting fragments may be self-sustainable if the production within the fragments is readjusted and that the higher the percentage of renewable energy sources, the larger is the probability that a fragment is self-sustainable. This implies that renewable energy sources can enhance grid security.

Limitation: the research gives little insight on how the Nigeria electric grid, with its negative peculiarities, will perform when islanded.

According to Marcelo Gustavo Molina (2016), presented a detailed mathematical model of a three-phase grid-connected photovoltaic generator in “Modelling and Control of Grid-connected Solar Photovoltaic Systems”. The research showed model of the PV array uses theoretical and empirical equations together with data provided by manufacturers and meteorological data (solar radiation and cell temperature among others) to predict the PV array characteristic curve. MATLAB/Simulink was used to implement the model and control strategy of the PV generator (Molina, 2016).

Limitations: While this research gave deep insight into modelling and control of distributed generation systems integrated into the power grid using empirical methods, it did not explore the integration of PV systems into the power grid from system operations perspective.

The work “A Guidebook on Grid Interconnection and Islanded Operation of Mini-Grid Power Systems Up to 200 kW”, provided further insight in interconnection of existing mini-grids to national or regional energy infrastructure (Greacen et al., 2013). It focuses on issues related to connecting existing small renewable electricity (RE) generators to the utility grid. It was further stated that the merging of renewable energy systems with the power grids required standardized best practices and technologies to ensure safety, efficiency, reliability, and best value for mini-grid operators, utilities, and their customers.

Limitations: The study considered mini-grids up to 200kW and also integrated at the low voltage interface.

In addition, Xoubi (2015) studied the “Viability of a Utility-Scale Grid-Connected Photovoltaic Power Plant in the Middle East”. The study examines the technical and economic potential of utility-scale PV electricity generation in the Middle East (Xoubi, 2015). It concluded, based on its findings, that a utility-scale PV power

plant is a viable option in Jordan and that it is capable of fulfilling a sizable portion of the country's energy needs at a competitive cost.

Limitations: Focuses on energy yield and cost component of grid tied utility scale PV systems in the Middle East. The study does not capture the peculiarities of the Nigeria electric grid.

Furthermore, M Oman et al. (2019) designed and simulated a PV system operating in Grid connected and stand-alone modes in an area where there are frequent black outs. In their work "Design and Simulation of a PV System Operating in Grid-Connected and Stand-Alone Modes for Areas of Daily Grid Blackouts", the system which includes a storage battery block with a proper capacity to secure for continuous power supply of a residential house with a daily energy load of 10 kWh (Omar & Mahmoud, 2019). It was found the system was able to cover the total daily energy demands of the house including the outlined electricity cutoff hours. Matlab software was used to simulate the system, where the daily load curve, grid cutoff hours, and the monthly solar radiation are considered. The obtained simulation results show that the produced PV energy exceeds the load demands during nine months of the year, and thereby, a high battery state of charge (SOC) in the range of 73-84% is achieved.

Limitations: The research does not cover a global scope for load considerations, it used only a 10kWh load

D. O. Johnson and A. A. Ogunseye's work "Grid-Connected Photovoltaic System Design for Local Government Offices in Nigeria" designed a roof-mounted Grid-connected 148.5kWp Photovoltaic System with Energy Storage for use in a Local Government secretariat in Nigeria. The design was simulated using PV*SOL software to evaluate the system's production performance and to know the amount of electric power generation for every day of the year. The result shows that the PV system's daily production far exceeds energy demand in the building. (Johnson & Ogunseye, 2017)

Limitations: The research does not cover a global scope for load considerations. It does not reflect the islanded grid system.

M. Kesraoui et al also reflected the modeling and simulation of grid connected solar PV system in “Grid Connected Solar PV System: Modeling, Simulation and Experimental Tests” where a solar PV system was modeled, simulated and experimentally tested. Then simulation work of the current voltage (I-V) characteristics and efficiency by using MATLAB/IMULINK was performed and disturbances and cases like blackout, load disconnection and islanded system have been investigated. Results that have been obtained showed that the grid connected PV system responds adequately to all the applied disturbances.

Research Gaps.

The review of related works revealed the following gaps:

- iv. There is a notable lack of studies analyzing large-scale PV systems integrated with existing grid infrastructure.
- v. Most research provides limited insights into cost-related aspects of large-scale PV systems within the Nigerian energy context.
- vi. There is insufficient data on the performance and operational behavior of utility-scale PV systems when integrated into the Nigerian grid.
- vii. Research on islanding sections of Nigeria’s 132kV grid remains limited.

1. CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

In this chapter, the procedure taken to actualize the project objectives is outlined. The materials, mathematical calculations and models will be fully discussed.

3.2 Materials

3.2.1 Physical Materials

i. A data collection printout, used to collate the various system parameters of the selected network for example impedance per unit length of the transmission lines. This printout was designed using Microsoft excel spreadsheet.

3.2.2 Software Tools.

- i. PowerWorld Simulator 20 Educational Version.
- ii. Microsoft Excel Spreadsheet.

PowerWorld

This is high level simulation software developed by PowerWorld Corporation that deploys graphic user interface capabilities in the modeling and analysis of power systems. Some of its uses include

- Modeling
- Simulation
- Visualization
- Developing Scientific graphics

Microsoft Excel Spreadsheet

This Microsoft-developed application is utilized in this project for data tabulation, analysis results, and, in some cases, graphical presentations.

Data collection template

The template in Table 3.1 was used to collect the data of the generation stations, transmission lines, inter bus transformers and loads that are connected to the chosen network. The various parameters like voltage ratings, power ratings, voltage ratios, frequency etc.

Table 3.1: Data collection template.

GENERATORS							
S/N	GENERATOR	VOLTAGE RATING (kV)	POWER RATING (MW)	Voltage Magnitude (p.u)	ACTIVE POWER (p.u)	Qmax (p.u)	Qmin (p.u)
1							
TRANSFORMERS							
S/N	TRANSFORMER	VOLTAGE RATING (kV)	POWER RATING (MVA)	FREQUENCY (Hz)	PRI/SEC VOLTAGE RATIO	RESISTANCE (P.U)	REACTANCE (P.U)
1							
TRANSMISSION LINES							
S/N	TRANSMISSION LINE	VOLTAGE RATING (kV)	POWER RATING (MW)	FREQUENCY (Hz)	LENGTH (km)	RESISTANCE (P.U)	REACTANCE (P.U)
1							
LOADS							
S/N	LOAD CENTERS	VOLTAGE RATING (KV)	POWER RATING (MVA)	ACTIVE POWER (p.u)	REACTIVE POWER (p.u)		

Note this template was distributed in 2019 to the transmission company of Nigeria, Owerri work center, Alaoji Transmission station and Afam Generating stations. The systems controllers obliged with the system parameters and data of the networks.

3.3 METHODOLOGY

In this section the steps that will be taken to achieve the objectives of the project were presented.

3.3.1 Network Selection and Data Collection.

The approach taken before carrying out the performance analyses are shown below:

- i. The Nigeria Electric Grid Spanning Afam power station to Yenogoa transmission station was considered.
- ii. The generation stations, Gbarain PS and Afam PS were contacted and requisite data collected.
- iii. The transmission stations were contacted and the line and load profile data collected.
- iv. Meetings with system operators were held to discuss the need and the feasibility of the project.
- v. Data of cost components of the system were collected.

3.3.2 Procedure for the project.

The algorithm for the project is as stated below;

- i. Collection of data: this involves the data of the generation stations, transmission lines, inter-bus transformers and connected loads.

- ii. Model system in PowerWorld: This will include creating models of the network the system without Utility Scale PV systems and with PV systems integrated.
- iii. Carry out load flow analysis of the system: This will include load flow analysis of the system
 - a. Without PV systems integrated
 - b. With PV systems integrated
- iv. Develop a contingency list.
- v. Conduct contingency analysis.
- vi. Carry out cost analysis of the different plants.

3.3.3 Flow Charts

A flowchart represents a workflow or process. It is a diagrammatic representation of an algorithm, a step-by-step approach to solving a task. The flow chart in figure 3.1 depicts the procedure for the project.

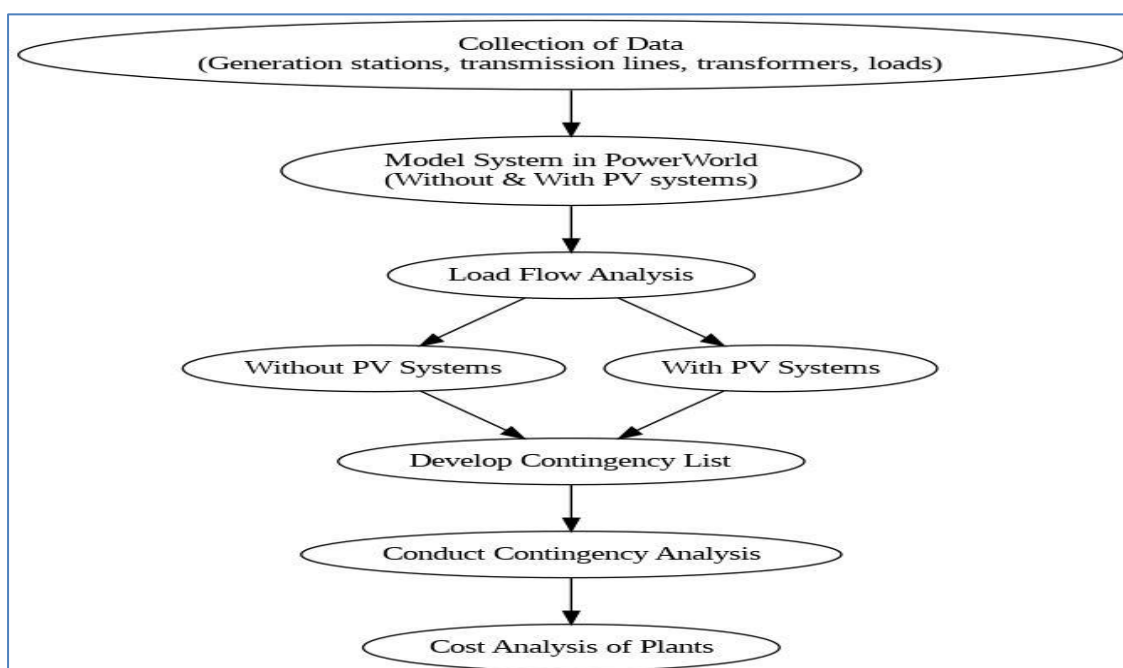


Figure 3.1: Flow chart for the procedure.

3.2.4 Data of Generation Stations.

Table 3.2 outlines the selected generation stations and their base specifications namely, Voltages in kilovolts and maximum active power rating. Note the maximum power rating is necessarily not the power the generating stations often export. For example, the Afam PS do not often exceed 1000MW.

Table 3.2: Generation station Voltage and power ratings (Niger Delta Power Holding Company).

S/N	Generating Stations		Type of Turbine	Voltage (kV)	Power (MW)
1	AFAM PS	AFAM VI	ST	330	200
			GT11	330	160
			GT12	330	150
			GT13	330	150
		AFAM IV	GT17	330	85
			GT18	330	85
		AFAM IPP	GT1	330	180
				TOTAL	1010
2	GBARAIN PS		GT	132	120

3.2.5 Inter-Bus Transformers.

The inter-bus transformers and the requisite specifications namely frequency, power rating in MVA, primary/secondary voltage ratios, Reactance and %impedance, for the analysis are populated in Table 3.3. Note the interbus transformers enable the Alaoji bus to be operated at 132kV, Hence the voltage level for this analysis is 132kV starting at Alaoji bus.

Table 3.3: Data of the inter-bus transformers (Transmission Company of Nigeria: TCN).

S/N	Transformers	Power (MVA)	Freq.	Pri/Sec Voltage Ratio	X P,u	%Z
1	330/132kV Tx at Alaoji (T2)	150	50	2.5	0.07573	11.36
2	330/132kV Tx at Alaoji (T3)	150	50	2.5	0.07573	11.36
3	330/132kV Tx at Alaoji (T4)	300	50	2.5	0.04523	13.57
4	330/132kV Tx at Afam (T1)	164	50	2.5	0.07074	11.46
5	330/132kV Tx at Alaoji (T2)	150	50	2.5	0.07573	11.36

3.2.6 Loads.

In Table 3.4 the maximum rated electrical loads (apparent, active and reactive power) at the 132/33kV substations are shown.

Table 3.4: Load Data ((Transmission Company of Nigeria).

S/N	Load Centers	Voltage (kV)	Power (MVA)	Active Power (MW)	Reactive Power (MVAR)
1	PH MAIN	132	180	144	36
2	ABA TS	132	187.5	150	37.5
3	UMUAHIA TS	132	80	64	16
4	OWERRI TS	132	160	128	32
5	AHOADA TS	132	80	64	16
6	YENOGOA TS	132	130	104	26

3.2.7 Transmission Lines

Table 3.5 shows the parameters of the transmission lines in the network, namely the transmission lines, bus voltages, maximum active power drawn, frequency, line length, reactance and resistance in per unit values.

Table 3.5: Transmission Line Data (Transmission Company of Nigeria).

S/N	Transmission Lines	Voltage kV	Power MW	Freq.	Length (km)	Resistance p.u	Reactance p.u
1	Afam- Alaoji Line 1	330	400	50	25	0.0009825	0.0073898
2	Afam- Alaoji Line 2	330	400	50	25	0.0009825	0.0073898
3	Afam- Alaoji Line 1	132	300	50	30	0.0047001	0.058801
4	Afam- Alaoji Line 2	132	300	50	30	0.0047001	0.058801
5	Alaoji-PH Line 1	132	144	50	37	0.0002121	0.0770005
6	Alaoji-PH Line 2	132	144	50	37	0.0002121	0.0770005
7	Alaoji-Aba Line 1	132	100	50	7	0.0011204	0.01412
8	Alaoji-Aba Line 2	132	100	50	7	0.0011204	0.01412
9	Alaoji-Umuahia Line1	132	80	50	57	0.0022401	0.016845
10	Alaoji-Umuahia Line2	132	80	50	57	0.0022401	0.016845
11	Alaoji-Owerri Line 1	132	100	50	60	0.0112947	0.1412004

12	Alaoji-Owerri Line 2	132	100	50	60	0.0112947	0.1412004
13	Owerri-Ahoada Line 1	132	100	50	74	0.0029084	0.021869
14	Owerri-Ahoada Line 2	132	100	50	74	0.0029084	0.021869
15	Ahoada-GbarainLine1 1	132	50	50	37.5	0.0014542	0.0109345
16	Ahoada-GbarainLine1 2	132	50	50	37.5	0.0014542	0.0109345
17	Gbarain-Yenogoa Line1	132	50	50	37.5	0.0014542	0.0109345
18	Gbarain-Yenogoa Line2	132	50	50	37.5	0.0014542	0.0109345

3.2.8 Single Line Diagrams of the Network

Figure 3.2 is the single line diagram of the power system network. This represents the model of the selected system as it is currently. It shows all the generating stations, buses and transformers of interest. Note for the purpose of clarity the protection equipment were excluded in the model.

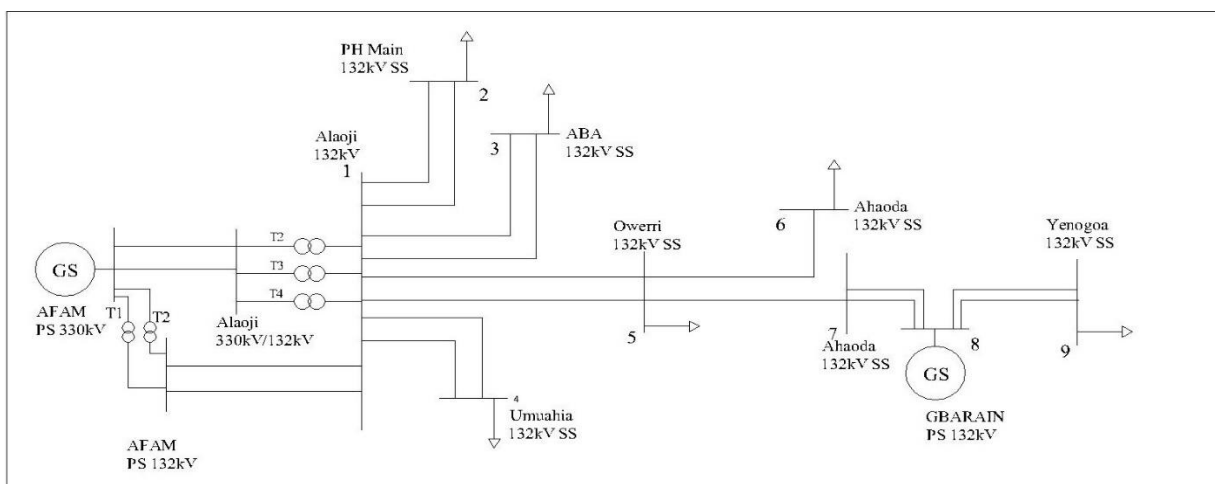


Figure 3.2: Single Line Diagram of the network

In Figure 3.3 diagram is the single line diagram of what the modified network will look like when integrated with PV systems. The PV plants are strategically located at the existing generation buses.

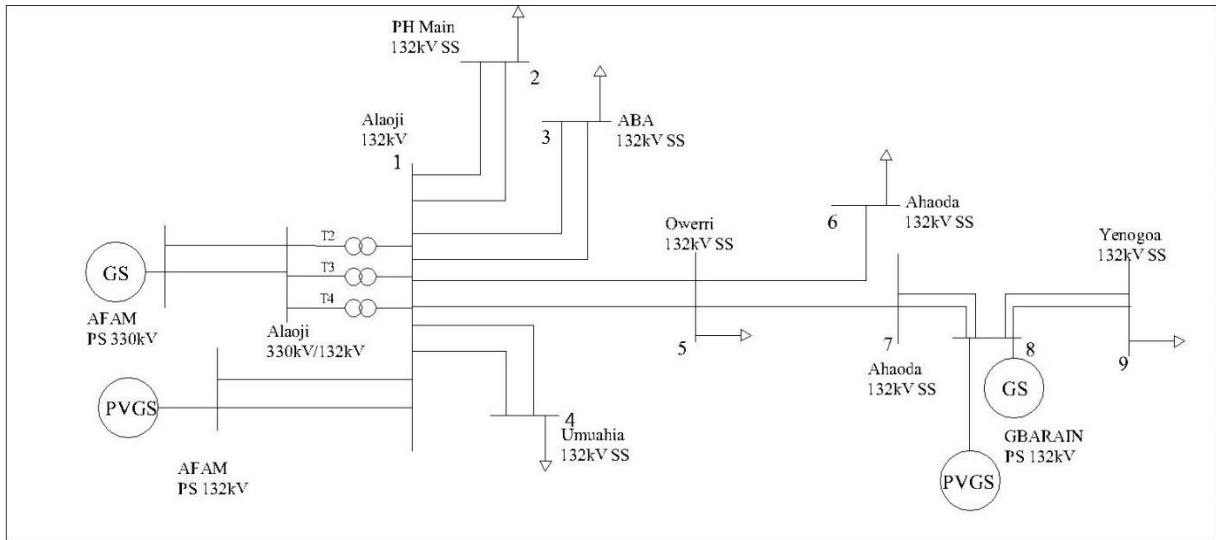


Figure 3.3: Single Line Diagram of the Modified Network.

3.2.9 Load Flow Analysis.

The derivation of power flow equations for a typical power system network are in Figure 3.4 is done with the following equations.

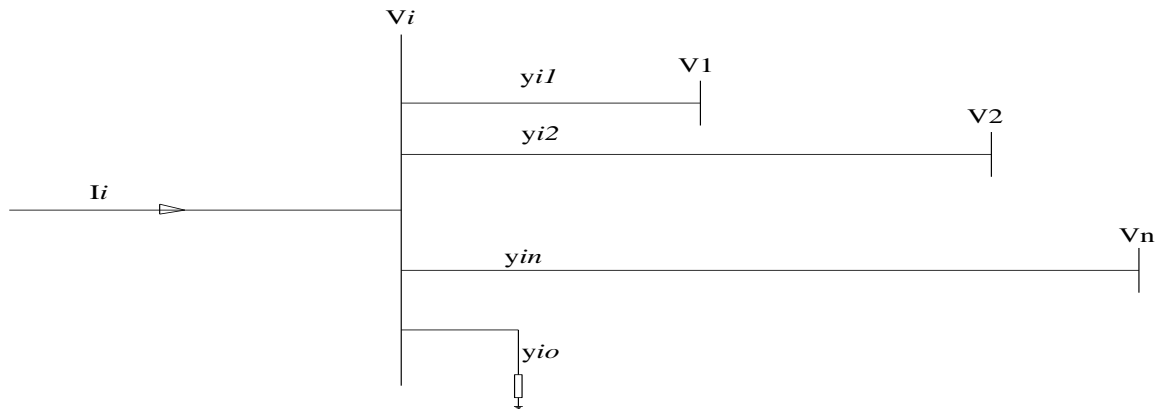


Figure 3.4: Typical Power System Network

The current entering the i th bus is given as

$$I_i = y_{i0} V_i + y_{i1} (V_i - V_1) + y_{i2} (V_i - V_2) + \dots + y_{ik} (V_i - V_k) \quad (3.1)$$

Collecting like terms in eqn 3.1, we have,

$$I_i = (y_{i0} + y_{i1} + y_{i2} + \dots + y_{ik})V_i - y_{i1}V_1 - y_{i2}V_2 - \dots - y_{ik}V_k \quad (3.2)$$

The term $(y_{i0} + y_{i1} + y_{i2} + \dots + y_{ik})$ is the self-admittance and the coefficients of V_1, V_2, \dots, V_k are the mutual admittances.

We simplify equation (3.2) as

$$I_i = \sum_{k=1}^n Y_{ik} V_k; i = 1, 2, \dots, n \quad (3.3)$$

The complex power injected into the i th bus of the power system is

$$S_i = P_i + jQ_i = V_i I_i^*; \text{ where } i = 1, 2, \dots, n \quad (3.4)$$

Where V_i is the i th bus voltage with respect to the earth and I_i^* is the conjugate of the current I_i . The power conjugate therefore becomes,

$$S_i = P_i - jQ_i = V_i^* I_i; \text{ where } i = 1, 2, \dots, n \quad (3.5)$$

Substituting I_i into equation 3.5

$$S_i = P_i - jQ_i = V_i^* \sum_{k=1}^n Y_{ik} V_k; \text{ where } i = 1, 2, \dots, n \quad (3.6)$$

Separating the real and reactive components of equation (3.6)

$$\text{Real power} = P_i = \text{Re} \{ V_i^* \sum_{k=1}^n Y_{ik} V_k \} \quad (3.7)$$

$$\text{Reactive power} = Q_i = -\text{Im} \{ V_i^* \sum_{k=1}^n Y_{ik} V_k \} \quad (3.8)$$

The Voltage and the admittance in polar form as given as

$$V_i = V_i \angle \delta_i, \quad V_i^* = V_i \angle -\delta_i \quad \text{and} \quad Y_{ik} = Y_{ik} \angle \theta_{ik}, \quad (3.9)$$

The real and reactive powers in polar form are expressed

$$\text{Real power} = P_i = V_i^* \sum_{k=1}^n Y_{ik} V_k \cos(\theta_{ik} + \delta_k - \delta_i) \quad (3.10)$$

$$\text{Reactive power} = Q_i = V_i^* \sum_{k=1}^n Y_{ik} V_k \sin(\theta_{ik} + \delta_k - \delta_i) \quad (3.11)$$

Due the non-linearity of the above equations, numerical methods are employed in the evaluation of the solutions to the equations. Several techniques exist like the Newton Raphson, Gauss Seidel and the Fast Decouple methods. The Newton Method is employed in this project.

The equations used for the Newton Raphson Method are as followed.

$$V_i = V_i e^{j\delta_i} \text{ also } V_i = V_i e^{-j\delta_i} \quad (3.12)$$

$$V_k = V_k e^{j\delta_k} \quad (3.13)$$

$$Y_{ik} = Y_{ik} e^{-j\delta_{ik}} \quad (3.14)$$

δ and θ are the phase angle and the admittance angle respectively.

Substituting equations (3.12), (3.13), (3.14) into equation (3.6)

$$S_i = P_i - jQ_i = \sum_{k=1}^n V_i V_k Y_{ik} e^{-j(\theta_{ik} + \delta_i - \delta_k)}; \text{ where } i = 1, 2, \dots, n \quad (3.15)$$

Therefore:

$$\begin{aligned} P_i &= \sum_{k=1}^n V_i Y_{ik} V_k \cos(\theta_{ik} + \delta_k - \delta_i) \\ &= V_i V_i Y_{ii} \cos\theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^n Y_{ik} V_i V_k \cos(\theta_{ik} + \delta_k - \delta_i) \end{aligned} \quad (3.16)$$

While

$$\begin{aligned} Q_i &= \sum_{k=1}^n V_i Y_{ik} V_k \sin(\theta_{ik} + \delta_k - \delta_i) \\ &= V_i V_i Y_{ii} \sin\theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^n Y_{ik} V_i V_k \sin(\theta_{ik} + \delta_k - \delta_i) \end{aligned} \quad (3.17)$$

3.2.10 PowerWorld Load Flow Simulation

The data of the various part of the network were input in the PowerWorld Simulator. This was used to calculate the voltages, power flows, the voltage angles of the busses. The PowerWorld base settings include

- i. Base MVA = 100

- ii. Voltage tolerance = $\pm 5\%$
- iii. Maximum number of iterations = 100
- iv. Range of Voltage angle = $\pm 10^\circ$
- v. Power Factor = 0.8
- vi. Slack bus voltage and angle = $1.05 \angle 0.00^\circ$
- vii. Slack Bus = Afam PS
- viii. Machine models: REG-C (Renewable Energy Generator- Controller) for PV generators and GENROU for Combined Cycle Gas Turbine.

The PowerWorld simulator is used to implement the system model and subsequently to run analyses of the models. The different line, bus, transmission and generation parameters are duly inputted the fields provided by the simulator.

In Figure 3.5 PowerWorld model of the network under analysis shows the one-line diagram of the entire selected network. The actually generating capacities of generation plants, inter-bus transformers, load buses and their capacities are modelled using the functionalities provided by PowerWorld.

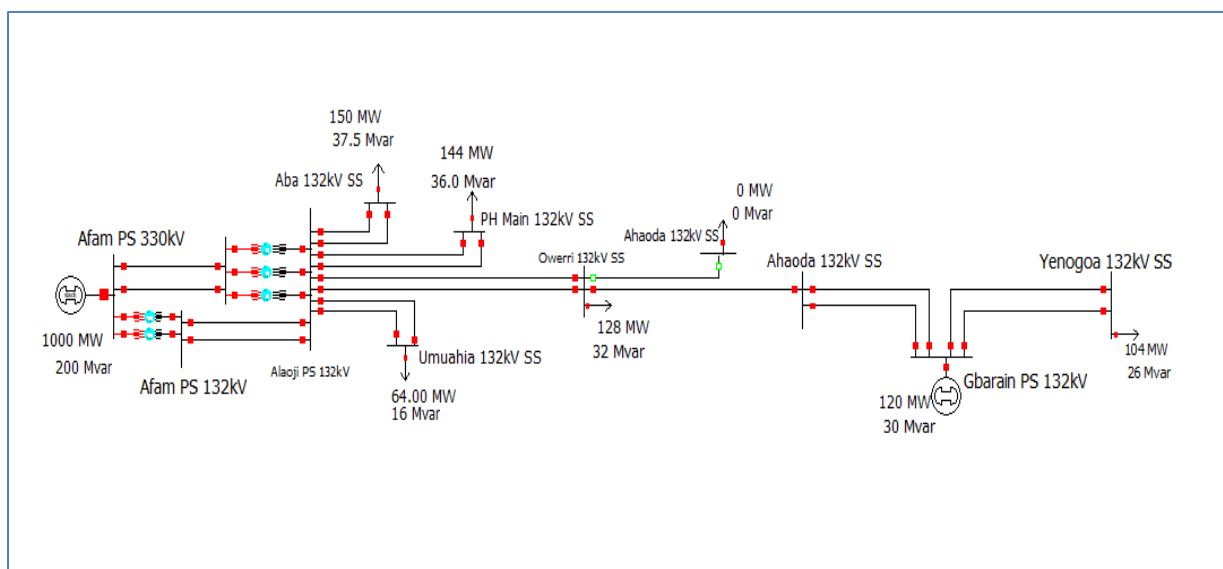


Figure 3.5: PowerWorld model of the network

The modified model sees an integration of an appropriate Utility scale PV systems at the generator buses and their parameters duly inserted. This is possible as PowerWorld provides structures that can accept basic parameters required for the analyses. Note the REG-C model was selected in the PowerWorld setup, with the real power capacities included.

Figure 3.6 depicts PowerWorld model of the modified network. The 500MW Photovoltaic generation plant was connected to Afam PS 132kV bus and another 120W Photovoltaic generating plant connected to Gbarain PS. This selected was made with the demand capacity at the load centers in mind.

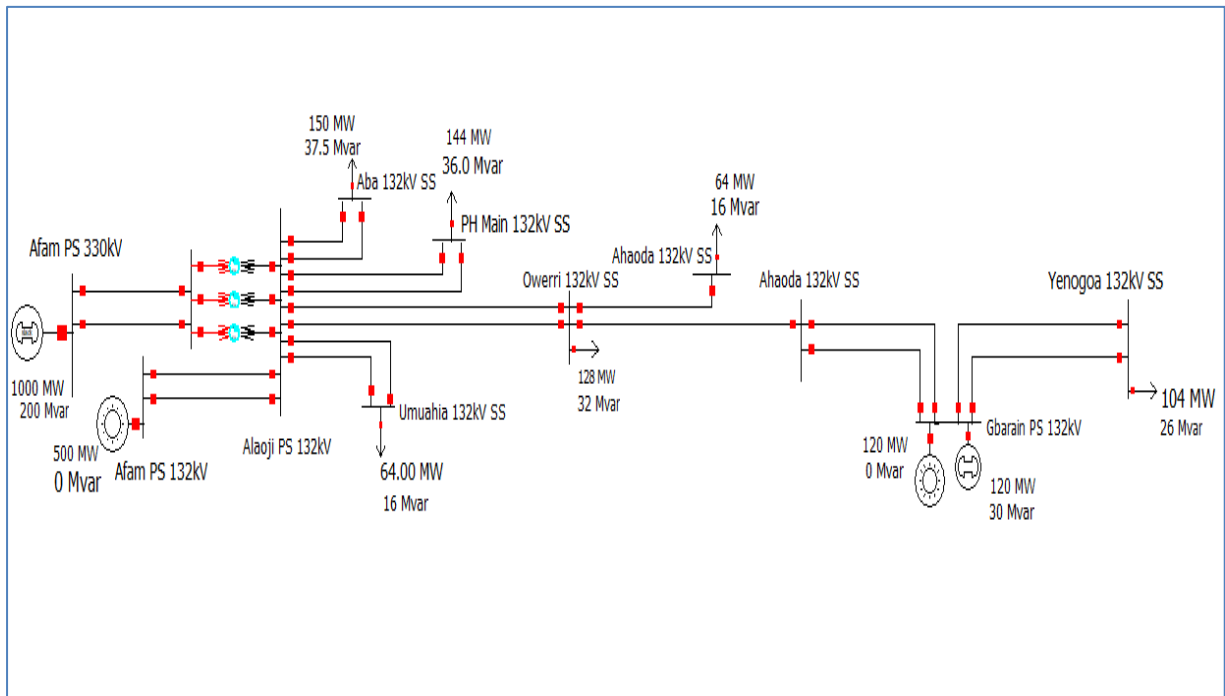


Figure 3.6: PowerWorld Model of the Network with PV systems integrated.

PowerWorld allows for settings such as maximum and minimum power output (both active and reactive power), voltage regulation settings, machine models, governor types, general MVA base etc.

3.2.11 Contingency Analysis

Since the Photovoltaic system is still a budding development, it is crucial to explore the behaviour of the system under an unexpected or planned system outage to detect the weakness that the network will bear. Contingencies can exist as the result of the outages of the system elements such as: generator, network transmission lines and system transformer for the purpose this work, we focus on the effect of outages of generating stations, particularly with the PV systems integrated and the effect of variability of the photovoltaic source on the system.

3.2.12 Contingency List

The contingency list is set in order to identify the effect of contingencies on the system operation and to experience which critical contingencies causes most violation of the system (Alex, 2015). In this project, the contingencies tested are

- i. Open Afam 330kV power station **without** the photovoltaic systems
- ii. Open Gbarain 132kV power station **without** the photovoltaic systems
- iii. Open Afam 330kV power station **with** the photovoltaic systems
- iv. Open Gbarain 132kV power station **with** the photovoltaic systems
- v. Zero Insolation at Afam 132kV Photovoltaic Station
- vi. Zero Insolation at Gbarain 132kV Photovoltaic Station

The PowerWorld simulator was used for the simulation of each of the contingencies.

3.2.13 Levelized Cost Energy Calculations

The levelized cost of electricity (LCoE) was evaluated for the two different power generation sources namely natural gas and solar energy. The Nigerian Electricity Regulation Council employs the US department of energy method of calculating LCOE. The formula is given below

$$LCoE = \frac{\text{Capital Cost} * CRF * (1 - T * D_{pv})}{8760 * \text{Capacity factor} * (1 - T)} + \frac{F_{om}}{8760 * \text{Capacity Factor}} + V_{om} + F_p * H_r \quad (3.18)$$

CRF = capital recovery factor, turning capital costs into annual values (if capital is financed at discount rate D)

F_{om} = Fixed Operation and maintenance Costs.

F_p = Fuel price.

H_r = Heat rate.

V_{om} = Variable Operation and maintenance Costs.

T = Tax rate, D_{pv} = Depreciation Factor

$$CRF = \frac{D * (1 + D)^N}{(1 + D)^N - 1} \quad (3.19)$$

D = Discount rate

N = Lifetime of System.

The cost components for evaluating LCoE are itemized in the next table.

The following values in table 3.6 are the cost components for LCoE evaluations of CCGT and PV systems. It represented the capital cost, the unit of cost measure, the two systems under consideration namely Combined cycle gas turbines (CCGT), steam turbines, Gas turbine and photovoltaic systems.

Table 3.6: Cost Components of the LCoE for GT and PV systems (Lazard, 2023)(TCN)

PARAMETERS	UNIT	GT	PV
Capital Cost	\$/kW	1300	1400
Fixed O & M	\$/kW-Yr	17	14
Variable O & M	\$/kWh	0.005	0
Capacity Factor	%	80	15
Discount Rate	%	11	9
Fuel Cost	\$/MMBtu	2.92	0
Depreciation	%	10	8
Tax Rate	%	5	0
Heat Rate	Btu/KWh	6900	0

Assuming $N = 20$ years and calculating the LCoE using equation (3.18) and (3.19)

1. For Open cycle gas turbine (GT).

$$\text{CRF} = \frac{0.11 \cdot (1.11)^{20}}{(1.11)^{20} - 1} = 0.1256$$

$$\text{LCoE} = \left(\frac{1300 \cdot 0.1256 \cdot (1 - (0.05 \cdot 0.1))}{8760 \cdot 0.8 \cdot (1 - 0.05)} \right) + \left(\frac{17}{8760 \cdot 0.8} \right) + 0.05 + \left(\frac{2.92}{10^6} \cdot 6900 \right)$$

$$= \mathbf{0.0970 \text{ \$/kWh}}$$

2. For PV systems

$$\text{CRF} = \frac{0.09 \cdot (1.09)^{20}}{(1.09)^{20} - 1} = 0.1095$$

$$\text{LCoE} = \left(\frac{1400 \cdot 0.1095 \cdot (1 - (0 \cdot 0.08))}{8760 \cdot 0.15 \cdot (1 - 0)} \right) + \left(\frac{14}{8760 \cdot 0.15} \right) + 0 + (0 \cdot 0) = \mathbf{0.1273 \text{ \$/kWh}}$$

CHAPTER FOUR

RESULTS AND DISCUSSION

RESULTS AND DISCUSSION

This chapter presents results and discussion of the objectives in chapter 3:

- i. Load flow analysis of the network without PV system
- ii. Load flow analysis of the network with PV system integrated
- iii. Contingency analysis of the network without PV system integrated.
- iv. Contingency analysis of the network with PV system integrated.
- v. LCoE calculation of the systems.

4.1 RESULTS FROM LOAD FLOW ANALYSIS OF THE NETWORK WITHOUT PV SYSTEM

Table 4.1 shows the values of the various key parameters of the buses under analysis when the photovoltaic systems are not integrated. The parameters of interest are Bus no, nominal voltage, per unit voltage, voltage angle, loads demanded and the generation from each station.

Table 4.1: Results of the PowerWorld Load Flow Simulation.

Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar
Afam PS 330kV	330	1.05	346.5	0.00			537.8	225.97
Afam PS 132kV	132	1.03063	136.043	-2.82				
Alaoji PS 132kV	132	1.01356	133.79	-5.10				
Umuahia 132kV SS	132	1.01151	133.519	-5.39	64	16		
Aba 132kV SS	132	1.01006	133.328	-5.68	150	37.5		
PH Main 132kV SS	132	0.998	131.736	-8.24	144	36		
Gbarain PS 132kV	132	0.96317	127.139	-12.02			120	30
Owerri 132kV SS	132	0.96164	126.936	-12.28	128	32		
Yenogoa 132kV SS	132	0.96089	126.837	-12.36	104	26		
Ahaoda 132kV SS	132	0.95593	126.182	-13.12	64	16		

From the results of the load flow analysis of the system as shown in the Figure 4.1, the following is deduced.

- a. All the bus voltage magnitudes are within the acceptable limit of $\pm 5\%$
- b. There are violations of bus voltage angles at buses 8,9,10, 11, 12, which are not within the $\pm 10^\circ$ range. This is explained by the fact that Gbarain PS is not sufficient to boost the real and reactive power supply at that end and there are **NO** reactors installed at the downstream station for compensation of losses. Hence the need for a system that can boost supply and compensate for losses. The Photovoltaic system comes as a viable option.
- c. The major active and reactive power demand is on Afam 330kV which will definitely have impact on system stability. Therefore, the system is always close to the tipping point and this explains clearly the partial collapses often experienced in this segment.

In Figure 4.1 and Figure 4.2 the graphical representation of the bus voltage p.u and voltage angle in degrees for each of the buses are plotted in bar charts. This shows the various voltage levels observed per bus during the analyses.

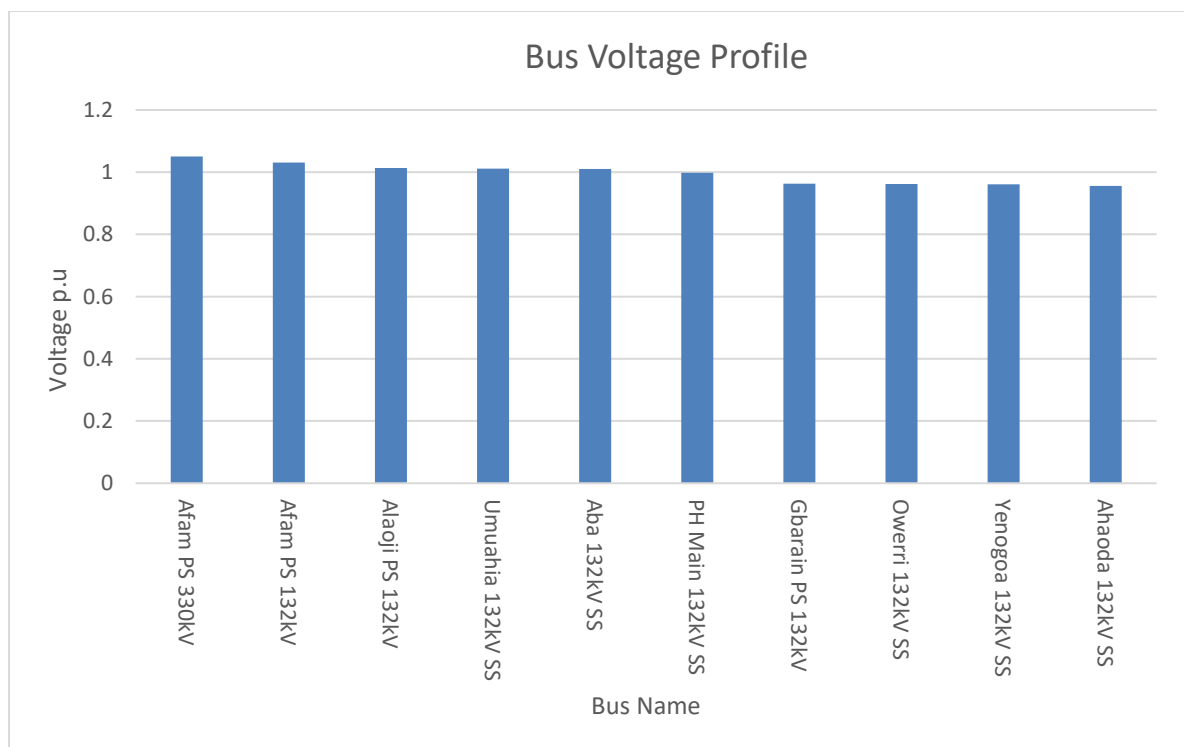


Figure 4.1: Bar chart of the Bus voltages without PV system.

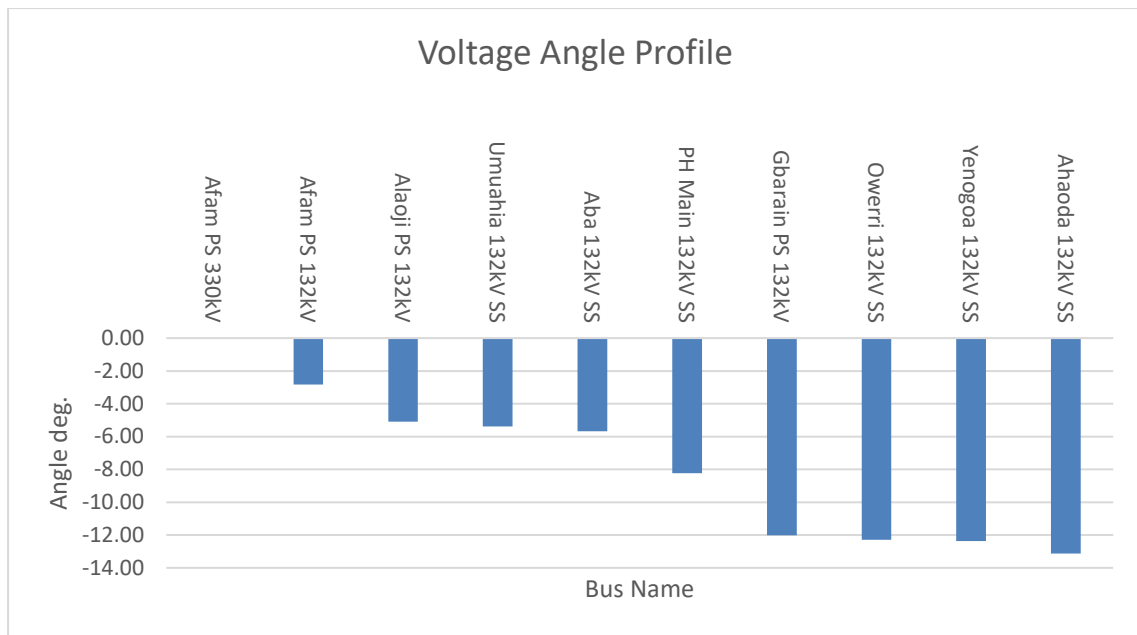


Figure 4.2: Bar chart of Voltage angles without PV system.

4.2 RESULTS FROM LOAD FLOW ANALYSIS OF THE NETWORK WITH PV SYSTEM

The results from LFA with the PV system integrated are tabulated with the value of several parameters shown. The parameters of interest again are Bus no, nominal voltage, per unit voltage, voltage angle, loads demanded and the generation from each station. In this case the PV systems are integrated.

Table 4.2: Results of the Power World Load Flow Simulation with PV system integrated

Bus No	Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar
1	Afam PS 330kV	330	1.05	346.5	0			17.32	191.4
2	Afam PS 132kV	132	1.03328	136.392	2.46			400	0
4	Alaoji TS 132kV	132	1.0173	134.283	-1.85				
5	Aba 132kV SS	132	1.0138	133.822	-2.43	150	37.5		
6	PH Main 132kV SS	132	1.0018	132.238	-4.97	144	36		
7	Umuahia 132kV SS	132	1.01525	134.013	-2.14	64	16		
8	Owerri 132kV SS	132	0.97648	128.895	-4	128	32		

9	Ahaoda 132kV SS	132	0.97086	128.153	-4.82	64	16		
10	Ahaoda 132kV SS	132	0.98055	129.433	-2.23				
11	Gbarain PS 132kV	132	0.98171	129.586	-1.79			240	30
12	Yenogoa 132kV SS	132	0.97948	129.291	-2.12	104	26		

The results in Table 4.2 show a clear improvement when the PV systems were integrated into the select segment of the grid. The following can be clearly seen.

- a. All the bus voltage magnitudes are within the acceptable limit of $\pm 5\%$, even with more improvement in values.
- b. There are no violations of buses angles as all are within the $\pm 10^\circ$ range. This is due to the fact that the PV systems assisted in improving the bus angle by supplying more active power.
- c. The reactive power demand on Afam PS was greatly reduced as the PV system relieved the station of that demand. This implies that when the PV is available we it can deliver most of the required real power in system. This will greatly impact on fuel cost as we will show later.

The bar chart in figure 4.3 showing the bus voltage profile after analysis presents an interesting observation.

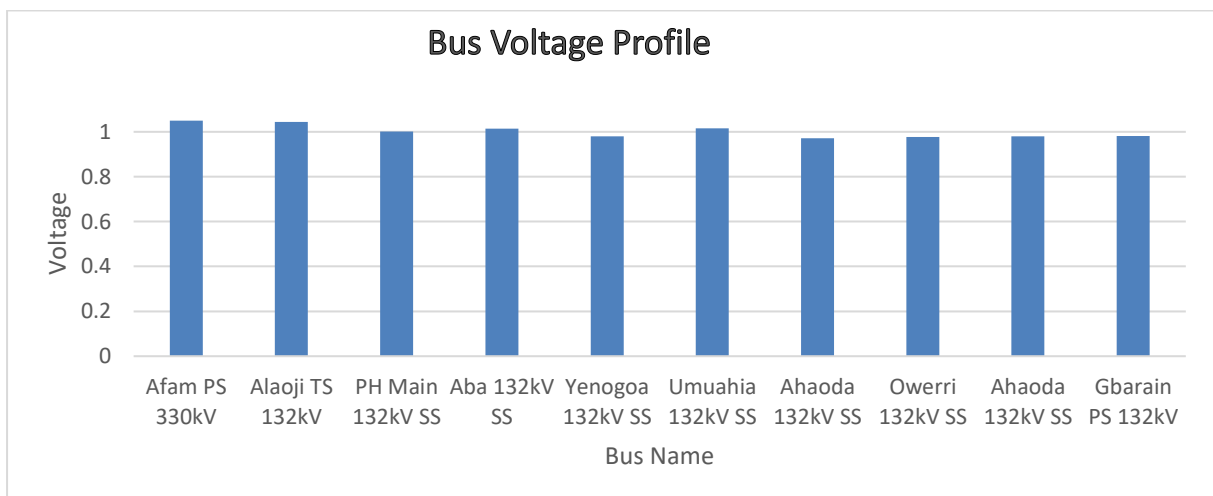


Figure 4.3: Bar chart of Bus Voltages with PV system

Again, a plot of voltage angle profile further interesting behaviour in Figure 4.4 of the various buses presents are marked difference upon integrating PV systems.

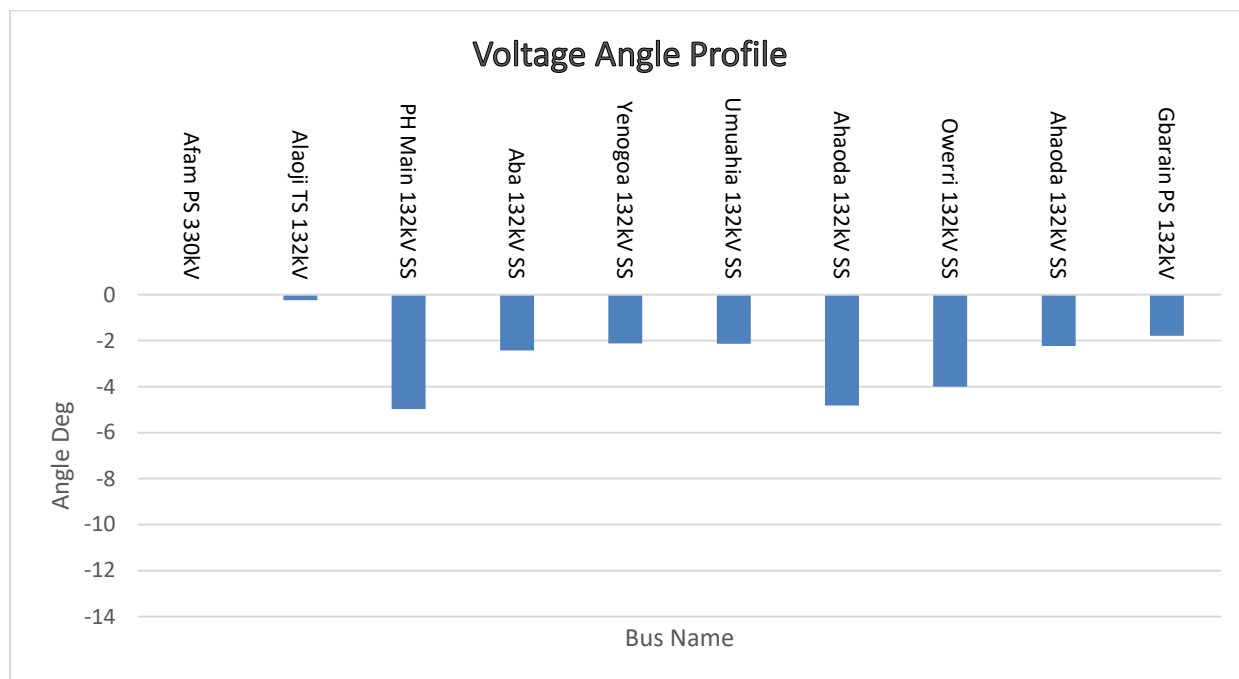


Figure 4.4: Bar chart of Voltage angles with PV system

4.3 RESULTS FROM CONTINGENCY ANALYSIS OF THE NETWORK WITHOUT PV SYSTEM

The contingency lists and the results of the simulations are shown in the tables 4.4. Here we see the various parameters considered namely the contingency label, violations, the least voltage encountered, the category, elements affected, value, limit etc.

Table 4.3: Results of the Power World contingency analysis without PV system

Contingency Label	Violations	Max Branch %	Min Volt
OPEN Afam 330kV PS	14	632.3	0.653
OPEN Gbarain 132kV PS	7	138.5	0.866

VIOLATION SUMMARY WHEN AFAM 330kV PS WAS OPENED WITHOUT PV					
Category	Element	Value	Limit	Percent	Nom kV Assoc.
Branch MVA	Owerri 132kV SS (8) -> Alaoji PS 132kV (4) CKT 1 at Owerri 132kV SS	247.28	125	197.82	132
Branch MVA	Owerri 132kV SS (8) -> Alaoji PS 132kV (4) CKT 2 at Owerri 132kV SS	247.28	125	197.82	132
Branch MVA	Ahaoda 132kV SS (10) -> Owerri 132kV SS (8) CKT 1 at Ahaoda 132kV SS	779.82	125	623.85	132
Branch MVA	Gbarain PS 132kV (11) -> Ahaoda 132kV SS (10) CKT 1 at Gbarain PS 132kV	404.37	62.5	646.99	132
Branch MVA	Gbarain PS 132kV (11) -> Ahaoda 132kV SS (10) CKT 2 at Gbarain PS 132kV	404.37	62.5	646.99	132
Bus Low Volts	Afam PS 330kV (1)	0.5676	0.95	59.75	330
Bus Low Volts	Afam PS 132kV (2)	0.5676	0.95	59.75	132
Bus Low Volts	Alaoji TS 132kV (3)	0.5676	0.95	59.75	330
Bus Low Volts	Alaoji TS 132kV (4)	0.5676	0.95	59.75	132
Bus Low Volts	Aba 132kV SS (5)	0.5618	0.95	59.13	132
Bus Low Volts	PH Main 132kV SS (6)	0.5378	0.95	56.61	132
Bus Low Volts	Umuahia 132kV SS (7)	0.5642	0.95	59.39	132
Bus Low Volts	Owerri 132kV SS (8)	0.8298	0.95	87.35	132
Bus Low Volts	Ahaoda 132kV SS (9)	0.8231	0.95	86.64	132

The table 4.4 shows the contingency analysis without PV system. The violation summary is presented with respect to the category of violation, element affected, value, nominal voltage etc

Table 4.4: Results of the Power World contingency analysis without PV system

VIOLATION SUMMARY WHEN GBARAIN 132 kV PS WAS OPENED WITHOUT PV					
Category	Element	Value	Limit	Percent	Nom kV Assoc.
Bus Low Volts	Yenogoa 132kV SS (12)	0.8661	0.95	96.23	132
Bus Low Volts	Owerri 132kV SS (8)	0.882	0.95	98	132
Bus Low Volts	Ahaoda 132kV SS (9)	0.8757	0.95	97.31	132
Bus Low Volts	Ahaoda 132kV SS (10)	0.8712	0.95	96.8	132
Bus Low Volts	Gbarain PS 132kV (11)	0.8686	0.95	96.51	132
Branch MVA	Alaoji PS 132kV (4) -> Owerri 132kV SS (8) CKT 2 at Alaoji PS 132kV	173.07	125	138.46	132
Branch MVA	Alaoji PS 132kV (4) -> Owerri 132kV SS (8) CKT 1 at Alaoji PS 132kV	173.07	125	138.46	132

The results in Figure 4.3 registered 14 violations when Afam PS was suddenly lost. The violations are severe as seen from the 9 bus voltage violations and 5 transmission line violations, thus whenever Afam PS is lost, the segment must collapse if any external source is not quickly brought in from the grid. Again, losing Gbarain PS recorded 5 bus voltage violations as shown in Table 4.4, which exceeded the $\pm 5\%$ voltage limits and overloaded Alaoji-Owerri line with above 30%, this could lead to loss of that transmission line thus compromising the system. Thus, this network as is, requires further redundancies as this contingency tested can trigger a system collapse of the entire grid.

4.4 RESULTS FROM CONTINGENCY ANALYSIS OF THE NETWORK WITH PV SYSTEM

In table 4.5, the contingency lists and the results of the simulations are shown in the Again, we see the various parameters considered namely the contingency label, no of violations, the least voltage encountered, the category, elements affected, value, limit etc.

Table 4.4: Results of the Power World contingency analysis with PV system

Contingency Label	Violations	Max Branch %	Min Volt	Max Volt	
Open Afam 330kV	3	108.8			
Open Gbarain 132kV	0				
Category	Element	Value	Limit	Percent	Nom kV
Branch MVA	Ahaoda 132kV SS (10) -> Owerri 132kV SS (8) CKT 1 at Ahaoda 132kV SS	135.79	125	108.63	132
Branch MVA	Gbarain PS 132kV (11) -> Ahaoda 132kV SS (10) CKT 1 at Gbarain PS 132kV	67.98	62.5	108.76	132
Branch MVA	Gbarain PS 132kV (11) -> Ahaoda 132kV SS (10) CKT 2 at Gbarain PS 132kV	67.98	62.5	108.76	132

The results showed improvements when the Afam 330kV PS was opened. The following could be deduced.

- a. There were only 3 violations which is far removed from the 13 violations recorded without PV system.
- b. There were no bus voltage violations.
- c. The percentage violations of the transmissions are negligible compared to the results got without PV systems. These lines overload can be remedied by simply increasing line capacities.

Hence, the PV systems will provide a high degree of stability when there is outage of any of the generation plants.

4.6 RESULTS FROM CONTINGENCY ANALYSIS OF THE NETWORK WHEN THERE IS ZERO INSOLATION AT THE PV POWER STATIONS

The basic challenge faced with PV systems is the variability of the source- the sun. We cannot certainly predict whether the sun will shine at the time we need it and

will definitely not be available at night. The results in Table 4.6 tested the effect of losing any of the PV systems.

Table 4.6: Results of the Power World contingency analysis when there is zero insolation.

Contingency Label	Violations	Max Branch %	Min Volt	Max Volt	
Zero Insolation @ Afam	3	108.8			
Zero Insolation @ Gbarain	2	131.1			
VIOLATIONS WHEN THERE IS ZERO INSOLATION AT AFAM PVGS					
Category	Element	Value	Limit	Percent	Nom kV
Branch MVA	Ahaoda 132kV SS (10) -> Owerri 132kV SS (8) CKT 1 at Ahaoda 132kV SS	135.79	125	108.63	132
Branch MVA	Gbarain PS 132kV (11) -> Ahaoda 132kV SS (10) CKT 1 at Gbarain PS 132kV	67.97	62.5	108.76	132
Branch MVA	Gbarain PS 132kV (11) -> Ahaoda 132kV SS (10) CKT 2 at Gbarain PS 132kV	67.97	62.5	108.76	132
VIOLATIONS WHEN THERE IS ZERO INSOLATION AT GBARAIN PVGS					
Category	Element	Value	Limit	Percent	Nom kV
Branch MVA	Alaoji TS 132kV (4) -> Owerri 132kV SS (8) CKT 1 at Alaoji PS 132kV	163.88	125	131.1	132
Branch MVA	Alaoji TS 132kV (4) -> Owerri 132kV SS (8) CKT 2 at Alaoji PS 132kV	163.88	125	131.1	132

The violations observed are transmission lines overload occasioned by the demand for more active power from

- a. Gbarain PS when there was zero insolation at Afam 132kV PVGS, Owerri-Ahoada line 2 and Gbarain-Ahoada Line1&2 being the trunk lines in this case (see appendix for branch flows).
- b. Afam PS when there was zero insolation at Gbarain PVGS, Alaoji-Owerri transmission lines. These can be mitigated again increasing line capacities of the affected lines.

4.6 RESULTS FROM COST ANALYSIS

The LCoE calculation in Chapter three was based on the variables collated. The tax rate was based only on the VAT for gas supply. The calculated LCoE for the open cycle gas turbines is **0.0970** \$/kWh, while LCoE for PV system is **0.1273** \$/kWh. While gas-fired power plants remain more cost-effective in the short term, PV systems offer a competitive alternative over the long run due to their decreasing costs and lower operating expenses.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The performance evaluation of an islanded Nigerian electricity network was conducted with a clear focus on predefined objectives. Using PowerWorld Simulator, both load flow analysis and contingency analysis were performed on a modified network incorporating a photovoltaic (PV) system.

In the load flow analysis of the network without PV system integration, significant variations in bus voltage angles were observed. Specifically, voltage angle deviations exceeded 10° , which could trigger relay operations, leading to the disconnection of multiple system segments. Additionally, the primary power demand was concentrated on Afam Power Station (PS), increasing the risk of instability in islanded conditions or in the event of an Afam PS outage.

Conversely, integrating PV systems into the network improved system performance. The PV system effectively supplied load demand when available, maintaining bus voltage angles within acceptable operating limits.

The contingency analysis further demonstrated that, without PV integration, the system exhibited significant instability, rendering intentional islanding impractical. The integration of PV systems mitigated this instability, reducing the number of severe violations from 14 to 3.

Furthermore, the levelized cost of electricity (LCoE) analysis provided insight into the economic implications of PV integration. At an exchange rate of 1,670.74 NGN/USD, the LCoE for conventional power sources was calculated at 162 NGN/kWh, whereas the LCoE for PV systems was 212 NGN/kWh. Despite the higher initial cost, the PV system presented a favorable long-term cost implication due to potential reductions in fuel dependency and operational costs.

5.2 RECOMMENDATIONS

This work is recommended for all power generation companies in Nigeria (GenCos). Once Nigeria power network is strengthened, the next challenge will be low generation capacity. This will lead to more electricity supply challenges in Nigeria. Generation companies can use the PV systems as relief stations when there is good insolation and gas supply is low. They can also use PV systems integrated to the grid to control electricity tariff because while deploying the system, cheaper electricity costs are likely going to be achieved.

5.3 RECOMMENDATIONS FOR FURTHER STUDIES

In view of the need to push this research across new frontiers, the following are recommendations for further study.

- a. The concept of islanding of power system in Nigeria electric grid with the focus on full integration renewable systems viz solar, wind etc., at transmission voltage levels should be further studied.
- b. Furthermore, more studies should be done on the deployment and performance of renewable energy systems, not limited to solar energy system, integrated into existing 33kV power grid in Nigeria.
- c. Again, research interests should be generated along lines the application of internet of things (IoT) to the existing grid with renewable energy systems integrated.

5.4 CONTRIBUTIONS TO KNOWLEDGE

This study contributes to knowledge in power system stability, renewable energy integration, and economic viability by:

1. Islanded Grid Stability Analysis – Identifies the instability of Nigeria's islanded power network without PV integration, particularly due to over-reliance on Afam Power Station.
2. Voltage Stability Improvement – Demonstrates that PV integration reduces voltage angle deviations, ensuring operational stability.

3. Enhanced Contingency Performance – Shows that PV systems reduce severe system violations from 14 to 3, improving fault tolerance.
4. Economic Viability of PV Systems – Provides real-world cost comparisons, showing an LCoE of 162 NGN/kWh for conventional power vs. 212 NGN/kWh for PV, supporting discussions on renewable energy investment.

REFERENCES

- ABB. (2017). *NEPLAN 360 - Power system analysis software*.
<http://search.abb.com/library/Download.aspx?>
- Abdallah, L., & El-Shennawy, T. (2013). Reducing carbon dioxide emissions from Electricity sector using smart electric grid applications. In *Journal of Engineering (United States)* (Vol. 2013, pp. 1–9). Hindawi Publishing Corporation. <https://doi.org/10.1155/2013/845051>
- African-EU Renewable Energy Corporation Programme. (2016). *Captive Power in Nigeria Comprehensive Guide to Project Development*. https://www.ctc-n.org/sites/www.ctc-n.org/files/resources/published_market_study_captive_power_nigeria_am1.pdf
- BHE RENEWABLES. (2019). *Just the facts, Topaz Solar Farms*. https://www.bherenewables.com/include/pdf/fact_sheet_topaz.pdf
- Bowen, T., Chernyakhovskiy, I., & Denholm, P. (2018). Grid-Scale Battery Storage: Frequently Asked Questions. *Nrel, 2013*, 1–8. www.greeningthegrid.org
- Buckley, T., & Shah, K. (2018). Solar is driving a global shift in electricity market. *Institute for Energy Economics and Financial Analysis (IEEFA)*, 1(5), 1–41. <http://irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017>
- Chinwuko, E. C., Mgbemena, C. O., Aguh, P. S., & Ebhota, W. S. (2011).

Electricity Generation and Distribution in Nigeria: Technical Issues and Solutions. *International Journal of Engineering Science and Technology (IJEST)*, 3(11), 7934–7941.

E El-Hawary, M. (2000). *Electrical Energy Systems*. CRC Press.

Emodi, N. V., & Yusuf, S. D. (2015). Improving Electricity Access in Nigeria: Obstacles and the Way Forward. *International Journal of Energy Economics and Policy*, 5(1), 335–351.

Energy Central News. (2024). *Nigeria's National Grid Collapse: Another Blackout as System Fails For the 7th Time in 2024*. Retrieved from <https://energycentral.com/news/>

ETAP. (2019). *Comprehensive, Integrated Suite of Power System Software Modules from Modeling to Operation*. <https://etap.com/docs/default-source/brochures/product-overview.pdf>

Faroosh, A. (2019). *Power Generation in Global Energy Demand* (pp. 1–6). IFP School, MOOC Energy Transition.

Federico Milano. (2006). *An Open Source Power System Analysis Toolbox (PSAT)*. http://faraday1.ucd.ie/archive/psat/psat_presentation.pdf

First Solar. (2018). *Agua Caliente Solar Project*. <http://www.firstsolar.com/en/Resources/Projects/Agua-Caliente-Solar-Project>

Foster, John, Wagner, L., & Bratanova, A. (2014). *LCOE models: A comparison of the theoretical frameworks and key assumptions* (Issue July).

Greacen, C., Engel, R., Quetchenbach, T., & Berkeley, L. (2013). *A Guidebook on*

Grid Interconnection and Islanded Operation of Mini - - - Grid Power Systems Up to 200 kW. International Atomic Energy Agency. (2018). *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050* (2018th ed., Issue 1). https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-1-38_web.pdf

International Renewable Energy Agency. (2018). *Renewable power generation costs in 2017 - Key findings and executive summary*. https://doi.org/10.1007/SpringerReference_7300

IRENA. (2019). Utility-Scale Batteries Innovation Landscape Brief. *International Renewable Energy Agency*, 7.

Johnson, D. O., & Ogunseye, A. A. (2017). Grid-connected photovoltaic system design for local government offices in Nigeria. *Nigerian Journal of Technology*, 36(2), 571. <https://doi.org/10.4314/njt.v36i2.33>

Julius, E., Olufemi, A. O., & Chuks, D. J. (2014). Challenges of sustaining off-grid power generation in Nigeria rural communities. *African Journal of Engineering Research*, 2(2), 51–57.

Karthikeyan, V., Rajasekar, S., Das, Vipin., Karuppanan, P., & Singh, A. Kumar. (2017). Grid-connected and off-grid solar photovoltaic system. *Green Energy and Technology*, 9783319501963, 125–157. https://doi.org/10.1007/978-3-319-50197-0_5

Kema OkakWu, I. (2017). Transient Stability Analysis of the Nigeria 330-kV δ (6), 79. <https://doi.org/10.11648/j.epes.20170606.11>

Kudal, Sandeep., Ankaliki, Shekhappa., Sunagar, Kiran., & Puthran, Vrutha. (2017). Comparative performance analysis of power systems. *2016 International Conference on Electrical, Electronics, Communication,*

- Computer and Optimization Techniques, ICEECCOT 2016*, 83–88.
<https://doi.org/10.1109/ICEECCOT.2016.7955190>
- Lambert-Lalitte, S. (2019). *The road towards a sustainable energy for all* (pp. 1–5). IFP School, MOOC Energy Transition.
- Lazard. (2018). *Levelized Cost of Energy and Levelized Cost of Storage 2018*.
<https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/>
- Madziga, M., Rahil, A., & Mansoor, R. (2018). Comparison between three off-grid hybrid systems (Solar photovoltaic, diesel generator and battery storage system) for electrification for gwakWani village, South Africa. *Environments - MDPI*, 5(5), 1–21.
<https://doi.org/10.3390/environments5050057>
- Mario Mureddu, Guido Caldarelli, Alfonso Damiano, Antonio Scala, & Hildegard Meyer-Ortmanns. (2016). islanding the power grid on the transmission level: less connections for more security. *Scientific Reports*, 6(1), 1–11.
- Molina, M. G. (2016). *Modelling and Control of Grid-connected Solar Photovoltaic Systems* (Wenping Cao & Y. Hu, Eds.). Intech.
<https://doi.org/10.5772/62578> NEPLAN. (2019). *Electricity*.
<https://www.neplan.ch/neplanproduct/en-electricity/>
- Nigerian Electricity Regulatory Commission. (2022). *2022 market competition report*. Retrieved from <https://nerc.gov.ng>
- Nigeria Electricity System Operator. (2019). *Home*. Retrieved March 4, 2025, from <https://www.nsong.org>
- Odewale, S. A., Sonibare, J. A., & Jimoda, L. A. (2012). *Electricity sector's contribution to greenhouse gas concentration in Nigeria*. Management of

Environmental Quality: An International Journal.
<https://doi.org/10.1108/MEQ-07-2016-0048>

Omar, M. A., & Mahmoud, M. M. (2019). Design and simulation of a PV system operating in grid-connected and stand-alone modes for areas of daily grid blackouts. *International Journal of Photoenergy*, 2019.
<https://doi.org/10.1155/2019/5216583>

Omonfoman, O. (2016). *Electricity Distribution Companies: The Challenges and Way*. <http://opinion.premiumtimesng.com/2016/01/04/electricity>

Onojo, O. J., Inyama, K., & Ononiwu, G. C. (2015). Contingency Analysis of the Nigeria 330kv Post-Reform Integrated Power System Using Power World Simulator. *Asian Journal of Natural & Applied Sciences*, 4(2).

Onojo, O. J., Ononiwu, G. C., & Okozi, S. O. (2013). Analysis of Power Flow of Nigerian 330Kv Grid System (Pre and Post) Using Matlab. *European Journal of Natural and Applied Sciences*, 1(2), 59–66.

Paul Breeze. (2010). *The Cost of Power Generation. The current and future competitiveness of renewable and traditional technologies*.
[http://lab.fs.uni-lj.si/kes/erasmus/The Cost of Power Generation.pdf](http://lab.fs.uni-lj.si/kes/erasmus/The%20Cost%20of%20Power%20Generation.pdf)

PowerWorld Corporation. (2019). *PowerWorld – The Visual Approach to Electrical Power Systems*. <https://www.powerworld.com/>

PowerWorld Corporation. (2020). *Machine Model: GENROU*.
https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Machine%20Model%20GENROU.htm

PricewaterhouseCoopers. (2017). *the World in 2050: PwC*. The Long View - How Will the Global Economic Order Change by 2050?
<https://www.pwc.com/gx/en/issues/economy/the-world-in-2050.html>

- Ramanaiah, P., & Rao, J. S. (2014). Contingency Analysis in Deregulated Power System Using FACTS Device (TCSC). *International Journal of Engineering Research and Development*, 10(10), 44–64. www.ijerd.com
- Roche, M. Y. (2017). Comparison of costs of electricity generation in Nigeria: A technical report. Heinrich Böll Stiftung Nigeria. <https://ng.boell.org/en/2017/06/19/comparison-costs-electricity-generation-nigeria-technical-report>
- Saadat, H. (1999). *Power System Analysis* - (B. Jones & L. Cox, Eds.; pp. 1–697). WCB/McGraw Hill. www.mhhe.com
- Salomon, C. P., Lambert-Torres, G., da Silva, L. E. B., Coutinho, M. P., & de Moraes, C. H. V. (2013). A hybrid particle swarm optimization approach for load-flow computation. *International Journal of Innovative Computing, Information and Control*, 9(11), 4359–4372.
- Sambo, A. (2008). Matching electricity supply with demand in Nigeria. *International Association for Energy Economics*, 32–36. <https://www.iaee.org/documents/newsletterarticles/408sambo.pdf>
- Samuel, I., Katende, J., Daramola, S. A., & Awelewa, A. (2014). Review of System Collapse Incidences on the 330-kV Nigerian National Grid. *International Journal of Engineering Science Invention*, 3(4), 55–59. www.ijesi.org55%7C
- Tavakoli, A. (2017). How Precisely «Kaya Identity» Can Estimate GHG Emissions: A Global Review. *Jordan Journal of Earth and Environmental Sciences*, 8(2), 91–96.
- The Paris Agreement* | UNFCCC. (2018). <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

- The World Bank Group. (2006). *Technical and Economic Assessment of Off-Grid, Mini-Grid and Grid Electrification Technologies Annexes*. <http://siteresources.worldbank.org/EXTENERGY/Resources/336805-1157034157861/ElectrificationAssessmentRptAnnexesFINAL17May>
- Transmission Company of Nigeria. (2019). *About us*. Retrieved February 25, 2019, from <https://tcn.org.ng/about/>
- Uche, O. C., Chimaobi, U. L., & Nelson, O. O. (2018). Analysis of Nigeria Power System Voltage Collapse Incidences From 2000 To 2017. *Journal of Electrical and Electronics Engineering*, 13(2), 28–34. <https://doi.org/10.9790/1676-1302012834>
- Ugochukwu K. Elinwa, John Emmanuel Ogbaba, & O. Philips Agboola. (2021). Cleaner energy in Nigeria residential housing. *Results in Engineering*, 9(100103).
- UNDESA. (2017). *World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100*. <https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html>
- Donev, J. M. K. C., et al. (2024). *Energy Education*. Retrieved from <https://energyeducation.ca>
- U.S. EIA. (2019). *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019*. Independent Statistics & Analysis. <http://www.eia.gov/outlooks/aeo/assumptions/>
- V.Raghavendra. (2017). *With Kurnool solar park, State takes a giant leap*. The Hindu. <https://www.thehindu.com/todays-paper/tp-national/tp-andhrapradesh/with-kurnool-solar-park-state-takes-a-giant-leap/article18289685.ece>

Vulin, D., Miličević, K., & Burulic, Z. (2011). Simulation of impact of a wind farm on the grid stability using PowerWorld Simulator. *Recent Advances in Signal Processing, Computational Geometry and Systems Theory - ISCGAV'11, ISTASC'11, August 2011*. World Nuclear Association. (2020). *Where does our electricity come from? - World Nuclear Association*. <https://www.world-nuclear.org/nuclear-essentials/where-does-our-electricity-come-from.aspx>

Xoubi, N. (2015). Viability of a Utility-Scale Grid-Connected Photovoltaic Power Plant in the Middle East. *Journal of Applied Sciences*, 15(11), 1278–1287. <https://doi.org/10.3923/jas.2015.1278.1287>

APPENDIX

BRANCH FLOWS WITHOUT PV											
From Number	From Name	To Number	To Name	Branch Device Type	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Afam PS 330kV	2	Afam PS 132kV	Transformer	75.2	30.6	81.2	162	50.1	0	4.23
1	Afam PS 330kV	2	Afam PS 132kV	Transformer	70.2	28.6	75.8	150	50.6	0	3.95
1	Afam PS 330kV	3	Alaoji PS 132kV	Line	196.2	83.4	213.2	500	42.6	0.41	3.05
1	Afam PS 330kV	3	Alaoji PS 132kV	Line	196.2	83.4	213.2	500	42.6	0.41	3.05
2	Afam PS 132kV	4	Alaoji PS 132kV	Line	72.7	25.5	77.1	300	25.7	0.26	3.29
2	Afam PS 132kV	4	Alaoji PS 132kV	Line	72.7	25.5	77.1	300	25.7	0.26	3.29
3	Alaoji PS 132kV	4	Alaoji PS 132kV	Transformer	106.6	43.7	115.2	150	76.8	0	9.25
3	Alaoji PS 132kV	4	Alaoji PS 132kV	Transformer	106.6	43.7	115.2	150	76.8	0	9.25
3	Alaoji PS 132kV	4	Alaoji PS 132kV	Transformer	178.4	73.2	192.9	300	64.3	0	15.49
4	Alaoji PS 132kV	5	Aba 132kV SS	Line	75.1	19.6	77.6	125	62.1	0.07	0.83
4	Alaoji PS 132kV	5	Aba 132kV SS	Line	75.1	19.6	77.6	125	62.1	0.07	0.83
4	Alaoji PS 132kV	6	PH Main 132kV SS	Line	72	22.3	75.4	180	41.9	0.01	4.26
4	Alaoji PS 132kV	6	PH Main 132kV SS	Line	72	22.3	75.4	180	41.9	0.01	4.26
4	Alaoji PS 132kV	7	Umuahia 132kV SS	Line	32	8.2	33.1	100	33.1	0.02	0.18
4	Alaoji PS 132kV	7	Umuahia 132kV SS	Line	32	8.2	33.1	100	33.1	0.02	0.18
4	Alaoji PS 132kV	8	Owerri 132kV SS	Line	89.1	35.6	96	125	76.8	1.01	12.66
4	Alaoji PS 132kV	8	Owerri 132kV SS	Line	89.1	35.6	96	125	76.8	1.01	12.66
8	Owerri 132kV SS	9	Ahaoda 132kV SS	Line	64.1	17	66.4	125	53.1	0.14	1.04
8	Owerri 132kV SS	10	Ahaoda 132kV SS	Line	-15.9	-3.2	16.2	125	13	0.01	0.06

10	Ahaoda 132kV SS	11	Gbarain PS 132kV	Line	-8	-1.7	8.1	62.5	13	0	0.01
10	Ahaoda 132kV SS	11	Gbarain PS 132kV	Line	-8	-1.7	8.1	62.5	13	0	0.01
11	Gbarain PS 132kV	12	Yenogoa 132kV SS	Line	52	13.3	53.7	62.5	86	0.05	0.34
11	Gbarain PS 132kV	12	Yenogoa 132kV SS	Line	52	13.3	53.7	62.5	86	0.05	0.34

BRANCH FLOWS WITH PV											
From Number	From Name	To Number	To Name	Branch Device Type	MW From	Mvar From	MVA From	Lim MV A	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Afam PS 330kV	2	Afam PS 132kV	Transformer	-65.9	26.2	70.9	162	43.8	0	3.23
1	Afam PS 330kV	2	Afam PS 132kV	Transformer	-61.6	24.5	66.3	150	44.2	0	3.02
1	Afam PS 330kV	3	Alaoji PS 132kV	Line	72.4	70.3	100.9	500	20.2	0.09	0.68
1	Afam PS 330kV	3	Alaoji PS 132kV	Line	72.4	70.3	100.9	500	20.2	0.09	0.68
2	Afam PS 132kV	4	Alaoji PS 132kV	Line	136.3	22.3	138.1	300	46	0.84	10.5
2	Afam PS 132kV	4	Alaoji PS 132kV	Line	136.3	22.3	138.1	300	46	0.84	10.5
3	Alaoji PS 132kV	4	Alaoji PS 132kV	Transformer	39.4	37.9	54.6	150	36.4	0	2.07
3	Alaoji PS 132kV	4	Alaoji PS 132kV	Transformer	39.4	37.9	54.6	150	36.4	0	2.07
3	Alaoji PS 132kV	4	Alaoji PS 132kV	Transformer	65.9	63.5	91.5	300	30.5	0	3.47
4	Alaoji PS 132kV	5	Aba 132kV SS	Line	75.1	19.6	77.6	125	62.1	0.07	0.82
4	Alaoji PS 132kV	5	Aba 132kV SS	Line	75.1	19.6	77.6	125	62.1	0.07	0.82
4	Alaoji PS 132kV	6	PH Main 132kV SS	Line	72	22.2	75.4	180	41.9	0.01	4.23

4	Alaoji PS 132kV	6	PH Main 132kV SS	Line	72	22.2	75.4	180	41.9	0.01	4.23	
4	Alaoji PS 132kV	7	Umuahia 132kV SS	Line	32	8.2	33.1	100	33.1	0.02	0.18	
4	Alaoji PS 132kV	7	Umuahia 132kV SS	Line	32	8.2	33.1	100	33.1	0.02	0.18	
4	Alaoji PS 132kV	8	Owerri 132kV SS	Line	28.6	27.6	39.8	125	31.8	0.17	2.16	
4	Alaoji PS 132kV	8	Owerri 132kV SS	Line	28.6	27.6	39.8	125	31.8	0.17	2.16	
8	Owerri 132kV SS	9	Ahaoda 132kV SS	Line	64.1	17	66.4	125	53.1	0.13	1.01	
8	Owerri 132kV SS	10	Ahaoda 132kV SS	Line	-	135.2	1.9	135.2	125	108.6	0.56	4.19
10	Ahaoda 132kV SS	11	Gbarain PS 132kV	Line	-67.9	-1.1	67.9	62.5	108.8	0.07	0.52	
10	Ahaoda 132kV SS	11	Gbarain PS 132kV	Line	-67.9	-1.1	67.9	62.5	108.8	0.07	0.52	
11	Gbarain PS 132kV	12	Yenogoa 132kV SS	Line	52	13.3	53.7	62.5	86	0.04	0.33	
11	Gbarain PS 132kV	12	Yenogoa 132kV SS	Line	52	13.3	53.7	62.5	86	0.04	0.33	

PowerWorld Load Flow Simulation Results

PowerWorld Simulator Sun Jul 21, 2019 8:47 AM Case: MySimul.PWB										
BUS	1	Afam PS 330kV	330.0	MW	Mvar	MVA	%	1.0500	0.00	1 1
GENERATOR	1		1396.00	349.00R	1439.0					
TO	2	Afam PS 132kV 1	75.19	30.60	81.2	50	1.0000TA	0.0		
TO	2	Afam PS 132kV 2	70.23	28.59	75.8	51	1.0000TA	0.0		
TO	3	Alaoji PS 132kV 1	196.19	83.39	213.2	43				
TO	3	Alaoji PS 132kV 2	196.19	83.39	213.2	43				
BUS	2	Afam PS 132kV	132.0	MW	Mvar	MVA	%	1.0306	-2.82	1 1
TO	1	Afam PS 330kV 1	-75.19	-26.37	79.7	49	1.0000NT	0.0		
TO	1	Afam PS 330kV 2	-70.23	-24.64	74.4	50	1.0000NT	0.0		
TO	4	Alaoji PS 132kV 1	72.71	25.50	77.1	26				
TO	4	Alaoji PS 132kV 2	72.71	25.50	77.1	26				
BUS	4	Alaoji PS 132kV	132.0	MW	Mvar	MVA	%	1.0136	-5.10	1 1
TO	2	Afam PS 132kV 1	-72.45	-22.22	75.8	25				
TO	2	Afam PS 132kV 2	-72.45	-22.22	75.8	25				
TO	3	Alaoji PS 132kV 1	-106.57	-34.48	112.0	75	1.0000NT	0.0		
TO	3	Alaoji PS 132kV 2	-106.57	-34.48	112.0	75	1.0000NT	0.0		
TO	3	Alaoji PS 132kV 3	-178.43	-57.74	187.5	63	1.0000NT	0.0		
TO	5	Aba 132kV SS 1	75.07	19.58	77.6	62				
TO	5	Aba 132kV SS 2	75.07	19.58	77.6	62				
TO	6	PH Main 132kV SS 1	72.01	22.26	75.4	42				
TO	6	PH Main 132kV SS 2	72.01	22.26	75.4	42				
TO	7	Umuahia 132kV SS 1	32.02	8.18	33.1	33				
TO	7	Umuahia 132kV SS 2	32.02	8.18	33.1	33				
TO	8	Owerri 132kV SS 1	89.13	35.56	96.0	77				
TO	8	Owerri 132kV SS 2	89.13	35.56	96.0	77				
BUS	8	Owerri 132kV SS	132.0	MW	Mvar	MVA	%	0.9616	-12.28	1 1
LOAD 1			128.00	32.00	131.9	DistGen		0.00	0.00	0.0
TO	4	Alaoji PS 132kV 1	-88.12	-22.90	91.0	73				
TO	4	Alaoji PS 132kV 2	-88.12	-22.90	91.0	73				
TO	9	Ahaoda 132kV SS 1	64.14	17.04	66.4	53				
TO	10	Ahaoda 132kV SS 1	-15.90	-3.24	16.2	13				
BUS	10	Ahaoda 132kV SS	132.0	MW	Mvar	MVA	%	0.9629	-12.07	1 1
TO	8	Owerri 132kV SS 1	15.91	3.30	16.2	13				
TO	11	Gbarain PS 132kV 1	-7.95	-1.65	8.1	13				
TO	11	Gbarain PS 132kV 2	-7.95	-1.65	8.1	13				
BUS	11	Gbarain PS 132kV	132.0	MW	Mvar	MVA	%	0.9632	-12.02	1 1
GENERATOR	1		120.00	30.00H	123.7					
TO	10	Ahaoda 132kV SS 1	7.95	1.66	8.1	13				
TO	10	Ahaoda 132kV SS 2	7.95	1.66	8.1	13				
TO	12	Yenogoa 132kV SS 1	52.05	13.34	53.7	86				
TO	12	Yenogoa 132kV SS 2	52.05	13.34	53.7	86				
BUS	12	Yenogoa 132kV SS	132.0	MW	Mvar	MVA	%	0.9609	-12.36	1 1
LOAD 1			104.00	26.00	107.2	DistGen		0.00	0.00	0.0
TO	11	Gbarain PS 132kV 1	-52.00	-13.00	53.6	86				
TO	11	Gbarain PS 132kV 2	-52.00	-13.00	53.6	86				

```

PowerWorld Simulator Sun Jul 21, 2019 9:11 AM Case: MySimu2.PWB
BUS 1 Afam PS 330kV 330.0 MW Mvar MVA % 1.0500 0.00 1 1
GENERATOR 1 1396.00 349.00R 1439.0
TO 2 Afam PS 132kV 1 -96.99 29.61 101.4 63 1.0000TA 0.0
TO 2 Afam PS 132kV 2 -90.60 27.66 94.7 63 1.0000TA 0.0
TO 3 Alaoji PS 132kV 1 52.68 72.65 89.7 18
TO 3 Alaoji PS 132kV 2 52.68 72.65 89.7 18

BUS 2 Afam PS 132kV 132.0 MW Mvar MVA % 1.0321 3.63 1 1
GENERATOR 1 500.00 0.00H 500.0
TO 1 Afam PS 330kV 1 96.99 -23.01 99.7 62 1.0000NT 0.0
TO 1 Afam PS 330kV 2 90.60 -21.49 93.1 62 1.0000NT 0.0
TO 4 Alaoji PS 132kV 1 156.20 22.25 157.8 195
TO 4 Alaoji PS 132kV 2 156.20 22.25 157.8 162
Mismatch 0.00 -0.00

BUS 4 Alaoji PS 132kV 132.0 MW Mvar MVA % 1.0162 -1.34 1 1
TO 2 Afam PS 132kV 1 -155.11 -8.51 155.3 192
TO 2 Afam PS 132kV 2 -155.11 -8.51 155.3 159
TO 3 Alaoji PS 132kV 1 -28.64 -37.61 47.3 32 1.0000NT 0.0
TO 3 Alaoji PS 132kV 2 -28.64 -37.61 47.3 32 1.0000NT 0.0
TO 3 Alaoji PS 132kV 3 -47.95 -62.97 79.1 26 1.0000NT 0.0
TO 5 Aba 132kV SS 1 75.06 19.57 77.6 62
TO 5 Aba 132kV SS 2 75.06 19.57 77.6 62
TO 6 PH Main 132kV SS 1 72.01 22.24 75.4 42
TO 6 PH Main 132kV SS 2 72.01 22.24 75.4 42
TO 7 Umuahia 132kV SS 1 32.02 8.18 33.1 33
TO 7 Umuahia 132kV SS 2 32.02 8.18 33.1 33
TO 8 Owerri 132kV SS 1 28.62 27.62 39.8 32
TO 8 Owerri 132kV SS 2 28.62 27.62 39.8 32

BUS 8 Owerri 132kV SS 132.0 MW Mvar MVA % 0.9753 -3.49 1 1
LOAD 1 128.00 32.00 131.9 DistGen 0.00 0.00 0.0
TO 4 Alaoji PS 132kV 1 -28.45 -25.45 38.2 31
TO 4 Alaoji PS 132kV 2 -28.45 -25.45 38.2 31
TO 9 Ahaoda 132kV SS 1 64.12 17.01 66.3 53
TO 10 Ahaoda 132kV SS 1 -135.19 1.91 135.2 108
Mismatch -0.03 -0.01

BUS 10 Ahaoda 132kV SS 132.0 MW Mvar MVA % 0.9794 -1.72 1 1
TO 8 Owerri 132kV SS 1 135.75 2.30 135.8 109
TO 11 Gbarain PS 132kV 1 -67.88 -1.15 67.9 109
TO 11 Gbarain PS 132kV 2 -67.88 -1.15 67.9 109

BUS 11 Gbarain PS 132kV 132.0 MW Mvar MVA % 0.9805 -1.27 1 1
GENERATOR 1 120.00 30.00H 123.7
GENERATOR 2 120.00 0.00H 120.0
TO 10 Ahaoda 132kV SS 1 67.95 1.67 68.0 109
TO 10 Ahaoda 132kV SS 2 67.95 1.67 68.0 109
TO 12 Yenogoa 132kV SS 1 52.02 13.33 53.7 86
TO 12 Yenogoa 132kV SS 2 52.02 13.33 53.7 86
Mismatch 0.06 -0.00

BUS 12 Yenogoa 132kV SS 132.0 MW Mvar MVA % 0.9783 -1.60 1 1
LOAD 1 104.00 26.00 107.2 DistGen 0.00 0.00 0.0
TO 11 Gbarain PS 132kV 1 -51.98 -13.00 53.6 86
TO 11 Gbarain PS 132kV 2 -51.98 -13.00 53.6 86
Mismatch -0.04 -0.00

```