Enhancing Power System Efficiency and Reliability Through Comprehensive Load Flow Analysis

Innocent Enya Echeng

Dept. of Electrical/ Electronic Engineering Technology, Federal Polytechnic Ugep, Cross River State, Nigeria.

ABSTRACT

This research presents a comprehensive load flow analysis of a power system to evaluate its electrical performance, efficiency, and reliability under operating conditions. The analysis focuses on determining real and reactive power flow, identifying system losses, and addressing challenges such as voltage instability and poor power quality. Electrical Transient Analyzer Program (ETAP) software was used to model and simulate the system using a single line diagram (SLD), with real operational data obtained from Port Harcourt Electrical Distribution Station and the Transmission Company of Nigeria, Niger Mill Station, Calabar. The research investigates critical issues affecting the network, including frequent power outages due to high transmission losses, under-voltage and over-voltage conditions, inactive buses, overloaded transformers, poor power factor, inadequate conductor sizing, and poor earthing practices. The system recorded a total load demand of 240.82 MW and 79.42 Mvar, while generators supplied 258.74 MW and 200.59 Mvar, indicating improved diversity under normal loading conditions. Initial analysis revealed significant power losses of 17.88 MW and 121.17 Mvar. Using the Fast Decoupled Newton-Raphson method in ETAP, corrective measures were applied by injecting 20 MW of real power into affected feeders. This resulted in a reduction of losses to 11.75 MW and 76.17 Mvar, achieving a 25.6% decrease in real power losses. Additionally, voltage profiles across buses were normalized, improving overall system stability. The study demonstrates the effectiveness of load flow analysis in optimizing power system performance and guiding future network expansion.

Keywords: Power Losses, Load Flow Analysis, Real and Reactive Power, Efficiency, Reliability

INTRODUCTION

Power system efficiency, encompassing generation, transmission, and distribution, is critical for sustainable energy practices. Efficient systems optimize resource utilization, minimize environmental impact, and enhance overall reliability. Continuous monitoring, technological advancements, and smart grid integration are vital for improving efficiency.

Reliability in power systems ensures consistent electricity delivery. Achieved through robust design, maintenance, and efficient operation, reliability requires resilient equipment, advanced technologies, and effective contingency planning. Continuous monitoring and quick fault response are essential for maintaining a reliable power supply. Load flow studies are used to ensure that electrical power transfer from generators to consumers through the grid system is stable, reliable and economic. The principal information obtained from the power flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line. The load flow study provides information about line and transformer loading (as well as losses) throughout the system and voltages at different points in the system for evaluation and regulation of the performance of the power systems. Further study and analysis of future expansion, stability and reliability of the power system network can be easily analyzed through this study. Increasing demand for the power and complexity of the power system network, power system study is a significant tool for a power system operator in order to take corrective actions in time. With the advent of digital computers, load flow solutions were obtained using network analyzers.

(Prabhu, *et. al.*, 2016). The flow of active and reactive power is known as load flow or power flow. Load flow analysis is an important tool used by power engineers for planning and determining the steady state operation of a power system. Power flow studies provide a systematic mathematical approach to determine the various bus voltages, phase angles, active and reactive power flows through different branches, generators, transformer settings and load under steady state conditions. The power system is modeled by an electric circuit which consists of generators, trans-mission network and distribution network (Mageshvaran, *et. al.*, 2008).

The main information obtained from the load flow or power flow analysis comprises magnitudes and phase angles of load bus voltages, reactive powers and voltage phase angles at generator buses, real and reactive power flows on transmission lines together with power at the reference bus; other variables being specified (Elgerd, 2012, and Kothari, and Nagrath, 2007) The resulting equations in terms of power, known as the power flow equations become non-linear and must be solved by iterative techniques using numerical methods. Numerical methods are techniques by which mathematical problems are formulated so that they can be solved with arithmetic operations and they usually provide only approximate solutions.

STATEMENT OF THE PROBLEM

The challenges in distribution networks include aging infrastructure, underside electrical cables, inadequate capacity, faulty transformers, lack of maintenance culture. Power quality concerns, and regulatory hurdles pose obstacles to optimizing and modernizing distribution networks. Insufficient power availability results in frequent outages and voltage fluctuations, impacting economic activities. Poor service delivery stems from aging infrastructure, inadequate capacity, and governance issues. Load shedding, caused by a demand-supply imbalance, is deteriorated by insufficient generation infrastructure, inadequate maintenance, and transmission constraints. These problems, influenced by population growth and industrialization, require investments in modernization, technology, and effective regulatory frameworks for a stable, efficient, and customer-centric power system. According to Innocent *et. al.,* 2025. The Diamond Hill bus network exhibited high efficiency with a power factor of 95.8% and stable voltage around 70.82%, despite handling heavy loads with a current of 141.4 kA. This high current indicates potential heavy loads or fault conditions, necessitating careful monitoring to prevent equipment overheating. The study identified key performance indicators such as active and reactive power losses, efficiency calculations, and voltage drops across various lines and transformers within the network.

AIM AND OBJECTIVES OF THE STUDY

This research is aimed at enhancing power system efficiency and reliability through comprehensive load flow analysis. with the following specific objectives;

i. Conduct a comprehensive load flow analysis of the selected power system network using ETAP to evaluate bus voltage profiles, generator and transformer loading, transmission-line loading, active and reactive power flows, and system power losses.
ii. Identify and assess inactive or underutilized generators and determine the major technical, operational, and economic factors responsible for their inactivity, and evaluate their effects on overall system performance and reliability.
iii. Identify critical buses, overloaded network components, voltage violations, and high-loss sections of the power system through the load flow analysis and determine their root causes.
iv. Evaluate the technical feasibility and optimal magnitude of distributed power injection into the network by conducting load flow simulations under different power-injection scenarios and determining the injection level required to improve voltage stability, reduce system losses, and relieve overloaded network components.
v. Investigate the impact of a 20 MW distributed power injection on the performance of the power system by comparing the base-case and corrective-action scenarios in terms of voltage profile, line and transformer loading, power losses, and power-flow distribution.
vi. Validate the effectiveness of the proposed corrective measure using ETAP simulation results by comparing the network performance before and after the integration of the proposed power injection.
vii. Develop recommendations for improving the efficiency, reliability, and operational performance of the selected power system network based on the results of the load flow analysis and corrective-action simulations.

SIGNIFICANT OF THE STUDY

Enhancing power system efficiency and reliability through comprehensive load flow analysis is crucial for several reasons. It provides a deep understanding of the system's operating conditions, allowing for informed decision-making in planning and operation. Improved efficiency means reduced energy losses, leading to cost savings and environmental benefits. Reliable load flow analysis helps prevent system failures, minimizes downtime, and enhances overall grid stability.

SCOPE AND LIMITATIONS OF THE STUDY

The scope of the work is to create other energy resources not to over-bulb the main utility transmission server and to create an alternate power source for Cross River state, and Calabar, the project is in line with the World Bank project to supply power to Calabar metropolis. Like the construction work going on in University of Calabar is a World Bank project to supply power to UNICAL communities.

i. The study assumes the validity and accuracy of the data sources. The analysis relies on information obtained from a network comprising 37 buses, 34 branches, 9 divert loads, and 1 power grid system in the Calabar region of Cross River state. It is presumed that the data collected from these sources is representative of the actual conditions within the power distribution network.

RESEARCH METHODOLOGY

The step-by-step methods involved in the analysis are

Network data collection Network modelling in ETAP 16.00 Bus classification and parameter specification Load modelling Base-case load flow Identification of inactive generators and network deficiencies Investigation of causes Sensitivity analysis of alternative power injections Technical selection of 20 MW, Corrective-action simulation ETAP validation Before-and-after comparison, Graphical voltage profile analysis Assessment of efficiency and reliability improvement**.**

LITERATURE REVIEW

Load Flow Analysis and Power System Performance

Load flow analysis is a fundamental tool for the planning, operation, and performance assessment of electric power systems. It provides information on bus voltage magnitudes and angles, active and reactive power flows, generation levels, transformer and transmission-line loading, and network power losses. These parameters are essential for identifying operational constraints and determining appropriate corrective measures for maintaining an efficient and reliable power supply (Glover, Sarma, & Overbye, 2012; Hadi, 2010).

The conventional load flow problem involves the solution of nonlinear algebraic equations describing the steady-state operating condition of a power network. Depending on the bus type, voltage magnitude, voltage angle, active power, and reactive power are specified or calculated. The commonly used numerical techniques include the Gauss-Seidel, Newton-Raphson, and Fast Decoupled Load Flow methods. Although these techniques have different computational characteristics, their effectiveness depends on the size, topology, loading condition, and characteristics of the network under investigation (Afolabi et al., 2015; Deepinder & Supreet, 2016).

Glover and Sarma (2002) and Glover et al. (2012) established the theoretical basis for load flow analysis and demonstrated its importance in determining steady-state system operating conditions. However, these works are primarily focused on the general principles and mathematical formulation of power system analysis rather than the diagnosis of specific operational problems in Nigerian distribution networks. Consequently, the application of these principles to actual networks requires reliable field data and appropriate network modelling.

Evaluation of Load Flow Solution Techniques

Several researchers have investigated the comparative performance of numerical load flow methods. Adejumobi, Adepoju, and Hamzat (2013) compared iterative techniques using the Nigerian 330 kV grid as a case study. Their study demonstrated the usefulness of iterative methods in solving Nigerian power system load flow problems. Adejumobi (2014) further examined numerical methods for load flow analysis using the Nigerian grid system. These studies are important because they demonstrate the applicability of conventional load flow techniques to Nigerian networks. However, their emphasis was largely on numerical solution techniques and grid-level analysis rather than detailed investigation of distribution-network deficiencies and corrective power injection.

Chatterjee and Mandal (2017) compared the Gauss-Seidel and Newton-Raphson methods and reported differences in convergence characteristics and computational performance. Similarly, Jagpreet and Rajni (2016) compared Newton-Raphson and Gauss-Seidel techniques for distributed transmission and generation networks, while Parwaiz, Jain, and Ansari (2019) conducted a comparative assessment of load flow methods using standard bus systems. These studies provide useful evidence regarding the computational suitability of different algorithms. However, the use of standard test systems limits their ability to capture the practical characteristics of geographically distributed Nigerian networks, including actual feeder configuration, transformer loading, inactive generating units, and local operating constraints.

Amerongen (1989) developed a general-purpose fast-decoupled load flow formulation, demonstrating the computational advantage of decoupled techniques for solving power flow problems. Bhowmik et al. (2011) also investigated the power perturbation method for load flow analysis, while Borzacchiello et al. (2016) proposed a unified formulation for iterative solvers. These contributions demonstrate continuing efforts to improve the speed, robustness, and flexibility of load flow computation. Nevertheless, improvements in numerical solution techniques alone do not resolve the practical network problems associated with poor voltage profiles, excessive losses, inactive generation, and inadequate power injection.

The literature therefore indicates that while the selection of an appropriate load flow algorithm is important, **the usefulness of load flow analysis ultimately depends on the quality of the network data, realistic modelling assumptions, validation, and the ability to translate simulation results into practical corrective actions**. This distinction is particularly relevant to the present study.

Load Flow Studies Using Real and Distribution Networks

The application of load flow analysis to actual distribution networks has received considerable attention. Abdulkareem et al. (2014), for example, investigated the Abule-Egba 33 kV distribution grid using real network simulations. Their study is particularly relevant because it demonstrates the importance of applying load flow analysis to an actual Nigerian distribution network rather than relying exclusively on standard test systems. The study assessed network operating conditions and provided practical information for evaluating the performance of the distribution system.

However, the Abule-Egba study primarily focused on assessing the existing distribution network and did not comprehensively investigate the causes of inactive generation or establish a systematic technical basis for selecting a specific distributed power injection as a corrective measure. This leaves an opportunity for further studies that combine network diagnosis with quantified corrective-action analysis.

Izuegbunam, Ojukwu, and Duruibe (2011) examined power flow and contingency assessment of the expanding Nigerian 330 kV grid using PowerWorld Simulator. Their work demonstrated the value of simulation-based analysis for identifying system constraints and evaluating network performance. However, the study concentrated on the transmission-grid level and contingency assessment rather than the detailed operational characteristics of a specific distribution network.

Afandi, Fadlika, and Gumilar (2017) investigated power-flow behaviour associated with power-system topology development. Their study highlights the importance of considering network configuration when assessing system performance. Similarly, Uzal et al. (2011) examined an electricity network under different operating scenarios, demonstrating the usefulness of scenario-based simulation. Nevertheless, these studies do not specifically address the combination of inactive generation, network losses, voltage deficiencies, and corrective distributed generation in the Calabar network.

Distribution-System Modelling, Load Characteristics and Voltage Performance

Accurate representation of load characteristics is essential to obtaining reliable load flow results. Indulkar and Ramalingam (2008) investigated load flow analysis with voltage-sensitive loads, highlighting the importance of considering load characteristics when determining network operating conditions. Golkar (2007) also examined load flow analysis for unbalanced three-phase radial distribution networks, demonstrating that distribution networks may require modelling approaches that reflect their actual operating characteristics rather than simplified assumptions.

Garces (2015) developed a linear three-phase load flow approach for distribution systems, addressing computational requirements associated with distribution-network analysis. These studies indicate that network characteristics, load representation, and system configuration can significantly influence the accuracy of load flow results.

Akinbulire et al. (2010) examined long-term electrical load forecasting using regression analysis, demonstrating the importance of accurate load information in power-system planning. Dada et al. (2016), in their audit of electricity generation at the University of Lagos, further demonstrated the importance of assessing actual generation and energy-use conditions when evaluating power-system performance.

Although these studies contribute to the understanding of load characteristics and distribution-system analysis, they do not directly investigate the effect of inactive generating units on voltage performance and network losses in the Calabar distribution network. The present study therefore extends the application of load flow analysis from general network assessment to **diagnosis of specific operational deficiencies and evaluation of a quantified corrective intervention**.

Simulation Tools for Power-System Analysis

Computer-based simulation has become an important component of modern power-system analysis because it enables complex networks to be represented and tested under different operating conditions. ETAP, MATLAB, and PowerWorld are among the tools used for modelling and analysing electrical networks.

PowerWorld has been applied to Nigerian grid studies, including the work of Izuegbunam et al. (2011), while ETAP-based approaches provide an integrated environment for modelling buses, generators, transformers, transmission lines, loads, and other network components. The major advantage of simulation environments is that they allow engineers to evaluate alternative corrective measures before their physical implementation.

However, simulation results are only as reliable as the quality of the network parameters and assumptions used in the model. A major limitation identified across several previous studies is insufficient description of system parameters, bus classifications, load assumptions, convergence criteria, and validation procedures. Consequently, a study based on an actual network should clearly document these aspects to improve reproducibility and confidence in the results.

Previous Research by the Authors and Research Progression

Innocent, Olasunmade, and Mede (2025) conducted a comprehensive analysis of bus load management and voltage regulation using Newton-Raphson and Fast-Decoupled techniques. Their study demonstrated the applicability of conventional load flow algorithms for evaluating voltage regulation and network performance.

The present research builds on that methodological foundation but extends the scope from comparative load flow techniques to **practical diagnosis and corrective improvement of an actual power distribution**

network. Specifically, the current study investigates inactive or underutilized generation, identifies network constraints associated with voltage and power losses, evaluates alternative levels of power injection, and determines the technical suitability of a 20 MW injection for improving network performance.

This progression is important because the objective is not merely to determine which numerical load flow method performs better. Rather, the objective is to use load flow analysis as a decision-support tool for identifying the causes of poor network performance and determining a technically justified intervention.

Critical Synthesis of Previous Studies and Research Gap

The reviewed literature demonstrates substantial development in load flow analysis, ranging from conventional numerical techniques to computer-based simulation and distribution-system modelling. However, three major limitations are evident.

First, a considerable number of studies have relied on standard IEEE test systems or theoretical networks (Dharamjit & Tanti, 2012; Parwaiz et al., 2019). Although such systems are useful for comparing algorithms, they may not adequately represent the operational conditions of actual Nigerian distribution networks.

Second, studies based on Nigerian networks have largely focused on load flow computation, transmission-grid assessment, voltage analysis, contingency studies, or network performance evaluation (Adejumobi et al., 2013; Abdulkareem et al., 2014; Izuegbunam et al., 2011). Comparatively limited attention has been given to linking **inactive generation, network deficiencies, power losses, voltage violations, and corrective distributed power injection within one integrated analysis**.

Third, previous studies generally provide limited technical justification for selecting a particular magnitude of distributed power injection. In many cases, corrective measures are proposed without systematically comparing alternative injection levels and quantifying their effects on voltage profile, network losses, and equipment loading.

MATERIALS AND METHOD

This study adopts a simulation-based methodology to assess the efficiency, reliability, and operational performance of the Calabar power distribution network through comprehensive load flow analysis. The study involves data collection, network modelling, load flow simulation, identification of system deficiencies, evaluation of inactive generators, determination of the appropriate power injection level, corrective-action simulation, and validation

Relevant technical data were collected for the Calabar sub-transmission and distribution network. The data include the network topology, transmission and distribution line parameters, bus data, transformer ratings and impedances, generator ratings, generator operating status, load demand, power factors, feeder information, and existing protection and operational characteristics.

The collected data were obtained from relevant power-sector sources and operational records and were used to develop the ETAP model of the study network. Particular attention was given to generators that were inactive or operating below their rated capacity in order to determine their contribution to the observed network deficiencies.

The Calabar power network was modelled using Electrical Transient Analyzer Program (ETAP 16.00). The model represents the major buses, generators, transmission/distribution lines, transformers, loads, and other relevant network components.

The network topology was developed according to the available single-line diagram and technical network data. The parameters entered into ETAP include generator ratings, transformer ratings, line impedances, bus voltage levels, load demand, power factors, and other component characteristics required for steady-state load flow analysis.

The model was configured to represent the operating condition of the network under the selected base-case scenario.

Bus Classification and System Parameters

The buses in the network were classified according to their electrical functions as:

- **Slack or swing bus:** The reference bus used to balance the active and reactive power mismatch in the network.
- **PV buses:** Buses associated with generators where active power and voltage magnitude are specified.
- **PQ buses:** Load buses where active and reactive power demands are specified.

The nominal voltage, generation capacity, load demand, transformer ratings, line parameters, and other system parameters were specified for each corresponding network component. The classification and parameter settings were maintained consistently for both the base-case and corrective-action simulations.

Load Modelling

The connected loads were represented according to their active and reactive power requirements. The load data were obtained from the available network records and converted to appropriate ETAP input parameters.

For the load flow simulations, the selected load model was maintained consistently between the base case and corrective-action cases to ensure that observed changes in system performance were attributable primarily to the proposed corrective measure rather than changes in load assumptions.

Load Flow Analysis

A steady-state load flow analysis was performed in ETAP 16.00 to determine the operating condition of the Calabar network. The analysis determines the bus voltage magnitude and angle, real and reactive power generation, real and reactive power flow through network branches, transformer loading, line loading, and total active and reactive power losses.

The Newton-Raphson-based load flow technique, together with the appropriate decoupled formulation available in the ETAP environment, was employed to determine the solution of the network power-flow equations. The convergence tolerance and maximum number of iterations were specified in ETAP and maintained consistently for all simulation cases.

The base-case simulation was first performed without the proposed corrective power injection. This provided the reference operating condition against which subsequent corrective-action results were compared.

Identification of Network Problems and Inactive Generators

The results of the base-case load flow were examined to identify:

1. buses with unacceptable voltage levels;
2. overloaded transmission and distribution branches;
3. overloaded transformers;
4. sections of the network with excessive active and reactive power losses;
5. abnormal power-flow patterns; and
6. inactive or underutilized generators.

The causes of generator inactivity were investigated based on the available technical and operational information. Possible factors considered include equipment condition, network constraints, operational limitations, insufficient generation availability, transmission constraints, and economic or operational considerations.

The effects of inactive generation units on voltage regulation, power losses, branch loading, and overall network reliability were subsequently evaluated.

Determination and Technical Justification of the 20 MW Power Injection

The selection of the 20 MW power injection was determined through technical load flow analysis rather than by arbitrary assumption. Different distributed-generation injection scenarios were simulated to examine their effects on network performance.

The tested scenarios may include incremental power injections such as 5 MW, 10 MW, 15 MW, 20 MW, and 25 MW, subject to the available generation and network capacity.

For each scenario, the following performance indicators were evaluated:

- minimum and maximum bus voltage;
- total active power losses;
- total reactive power losses;
- line loading;
- transformer loading;
- power-flow distribution; and
- number and severity of voltage violations.

The 20 MW injection was selected based on the simulation results and its ability to provide a technically significant improvement in network performance while avoiding unnecessary generation capacity and potential overvoltage or equipment-loading problems.

One-line diagram

The proposed injection station along Lemna Road aims to enhance the power supply in the Calabar metropolis feeder, ultimately injecting 60MW into the existing 11kV distribution network. The station features a gas-reactive system comprising four generators, each with a capacity of 5MW, totaling 20MW. These generators produce power at 0.415kV, which is then stepped up to 11kV using a 15MVA transformer. Additionally, to facilitate power transmission over longer distances, four 15kVA transformers are employed to further boost the voltage to 33kV. From there, power is distributed to various distribution centers, ultimately reaching end-users at 500kVA and 300kVA levels.

However, the project encountered setbacks due to errors in calculating the equipment ratings used for the voltage step-up process. This discrepancy led to inefficiencies in the system, hindering the intended power supply enhancement goals. To address this issue, thorough research into the knowledge gap is necessary.

The research focuses on understanding and rectifying the errors in equipment rating calculations, aiming to ensure the efficiency and effectiveness of the injection station. It involves a comprehensive analysis of the station's design, equipment specifications, and voltage transformation processes. Special attention is paid to identifying the root causes of the calculation errors and devising appropriate solutions to rectify them.

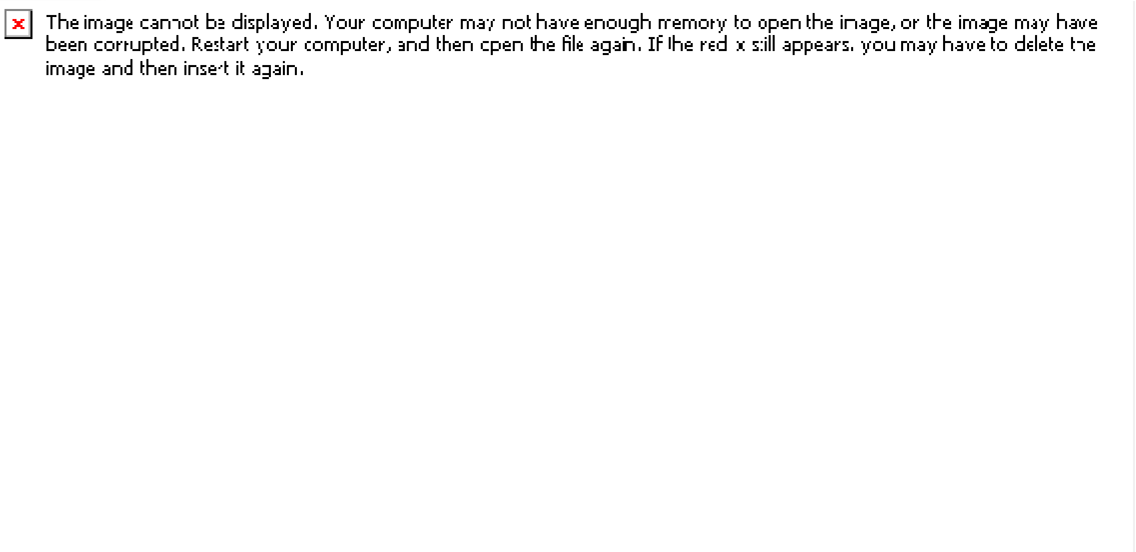

Figure 8.1: Single line diagram of Calabar power distribution network using ETAP software

Materials

The materials used for the analysis are: line input data like, tie power devices, impedance, Line/Cable/Busway, and transformers, bus data like Swing Bus, V-Control Bus, and load, a personal computer; Electrical transient analysis program (ETAP) programming codes using Fast decoupled load flow algorithms. Also, ETAP software was used for comparison/validation. The Fast Decoupled Load Flow method was applied for the distribution network under consideration. The Fast Decoupled method is the modified version of Newton Raphson Load flow method. The network was modeled in the Electrical Transient Analyzer program (ETAP software) for simulation purposes.

Method

Power flow analysis method is used extensively in the planning, design and operation of electrical systems, etc. Some basic information obtained from load flow studies are magnitude of voltages (V), phase angle of voltages (δ), active powers (P), reactive powers (Q), line power losses (Lpl). The numerical analysis involving the solution of algebraic simultaneous equations forms the basis for solution of the performance equations in computer aided electrical power system analyses e.g. for load flow analysis (Keyhani, *et. al.*, 1989). The first step in performing load flow analysis is to form the *Y*-bus admittance using the transmission line and transformer input data. The nodal equation for a power system network using *Y* bus can be written as follows:

$$I = YBusV \qquad (8.1)$$

Where;

I is the complex current

Y is the admittance bus

V is the voltage magnitude

The nodal equation can be written in a generalized form for an *n* bus system.

$$I_i = \sum_{j-1}^{n} Y_{ij} V_j \qquad (8.2)$$

Where;

Ii is the complex current at bus i

$\sum_{j=1}^{n} Y_{ij}$ is the summation over all buses (j) in the power system

$Y_{ij}$is the admittance between buses $i \ and \ j$

n are the total numbers of buses in the system?

The read and reactive power at bus I is,

$$P_i + JQi = ViI^* \quad (8.3)$$

Where;

P_i is the real power (measure in Watt W)?

jQi is the reactive power injected bus i (measure in Volt-Ampered, reactive VAR)

Vi is the voltage magnitude at the point i (measure in volt V)

I* is the complex conjugate of the current.

$$I_i = \frac{Pi - JQi}{Vi} \quad (8.4)$$

Substituting for I_i in terms of P_i and Q_i, the equation gives

$$\frac{Pi-JQi}{Vi} = V_i \sum_{j-1}^{n} Y_{ij} - \sum_{j-1}^{n} Y_{ij} \ V_j \quad (8.5)$$

The general forms of the various solution methods; Gauss-Seidel, Newton Raphson and Fast decoupled load flow.

Gauss-Seidel Method

This method is developed based on the Gauss method. It is an iterative method used for solving a set of nonlinear algebraic equations Keyhani, *et. al.,* (1989). The method makes use of an initial guess for the value of voltage, to obtain a calculated value of a particular variable. The initial guess value is replaced by a calculated value. The process is then repeated until the iteration solution converges. The convergence is quite sensitive to the starting values assumed. But this method suffers from poor convergence characteristics Abdulkareem, *et. al.,(*2014).

This is an iterative method which is used to solve Equation (3.5) for the value of Vi, and the iterative sequence becomes

$$V_i^{k+1} = \frac{1}{Y_{ii}}\left[\frac{P_i - JQ_i}{V_i^{(k)}} + \sum_{j=1}^{i-1} Y_{ij} \, V_j^{(k+1)} + \sum_{j=i+1}^{n} Y_{ij} \, V_j^{(k)}\right]$$

$$V_i^{(k+i)} = \frac{1}{Y_{ii}}\left[\frac{P_{i,sch} - JQ_{i,sch}}{V_i^{(k)*}} + \sum_{j=i}^{n} Y_{ij} \, V_j^{(k+1)}\right] \quad (8.6)$$

Using Kirchhoff current law, it is assumed that the current injected into bus i is positive, then the real and the reactive powers supply into the buses, such as generator buses, $P_{i,sch}$ and $jQ_{i,sch}$ have a positive value. The real and the reactive powers flowing away from the buses, such as load buses $P_{i,sch}$ and $Q_{i,sch}$ have a negative value. $P_i$and Q_i are solved from Equation (3.6) which gives

$$P_{i,sch} = \text{Real}\left[V_i^k \ \sum_{j=1}^{n} Y_{ij} \, V_j^K - \sum_{j=1}^{n} Y_{ij} \, V_i V_j\right] \quad (8.7)$$

$Q_{i,sch}$=Imaginary $\left[V_i^{(k)} \sum_{j=1}^{n} Y_{ij} - \sum_{j=1}^{n} V_i^{(k)}\right]$ (8.8)

The power flow equation is usually expressed in terms of the bus admittance matrix, using the diagonal elements of the bus admittance and the non-diagonal elements of the matrix, then the Equation (8.7) becomes,

$$P_i^{(k+1)} = Read\ \left[V_i^{(k)}\left\{V_i^{(k)} Y_{ii} + \sum_{j=1}^{n} Y_{ij} V_j^{(k+1)}\right\}\right] \quad j \neq 1$$

$$P_i^{(k+1)} = Read\left[\sum_{j=1}^{n} Y_{ij} V_i^{(k)} V_i^{(k+1)}\right] = \text{Read } \left[V_i^k \sum_{j=1}^{n} Y_{ij} V_j\right] \quad (8.9)$$

$$Q_i^{(K+1)} = \text{- Imaginary } \left[V_i^{(k)}\left\{V_i^{(k)} Y_{ii} - \sum_{j=1}^{n} Y_{ij} V_i^{(k+1)}\right\}\right]$$

$$Q_i^{(K+1)} = \text{- Imaginary}\left[V_i^{(k)}\left\{\sum_{j=1}^{i-1} Y_{ij} V_i^{(k+1)} + \sum_{j=1}^{n} Y_{ij} V_i^{(k)}\right\}\right]] \quad j \neq i \quad (8.10)$$

$$P_i = Read\ \left[V_i^K \sum_{j=1}^{n} Y_{ij} + V_j\right]$$

$$Q_i = -Im\ \left[V_i^K \sum_{j=1}^{n} Y_{ij} V_j\right]$$

$$P_i = JQ_i = V_i^k \sum_{j=1}^{n} Y_{ij} V_j \quad (8.11)$$

The admittance to the ground of line charging susceptance and other fixed admittance to ground are included into the diagonal element of the matrix.

Newton Raphson Method

This method was named after Isaac Newton and Joseph Raphson. The origin and formulation of Newton-Raphson method was dated back to late 1960s Amerongen, (1989). It is an iterative method which approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to the first approximation. It is the most iterative method used for the load flow because its convergence characteristics are relatively more powerful compared to other alternative processes and the reliability of Newton-Raphson approach is comparatively good since it can solve cases that lead to divergence with other popular processes Glover, and Sarma, (2002) If the assumed value is near the solution, then the result is obtained very quickly, but if the assumed value is farther away from the solution then the method may take longer to converge Hadi, (2010). This is another iterative load flow method which is widely used for solving nonlinear equations. The admittance matrix is used to write equations for currents entering a power system. Equation (8.3) above is expressed in a polar form, in which *j* includes bus *i*

$$I_i = \sum_{j-1}^{n} |Y_{ij}||V_j| < \theta_i + \delta_j \quad (8.12)$$

The real and reactive power at bus i is

$$P_i\text{-} JQ_i = V_i^* + I_i \quad (8.13)$$

Equation (3.13) is obtained from equations (3.14) and. (3.15).

$$P_i \text{ - } JQ_i = |\text{Vi}| < -\delta j \sum_{j-1}^{n} |Y_{ij}||V_j| < \theta_{ij} + \delta_j \quad (8.14)$$

The distinction between the real and imaginary parts can be obvious through the expansion of equation (8.12), which leads to equations (8.15) and (8.16).

$$P_i = \sum_{j-1}^{n} V_i |V_i||Y_{ij}| \text{ Cos } (\theta_{ij} - \delta j + \delta j \quad (8.15)$$

$$Q_i = -\sum_{j-1}^{n} |V_i| |V_i||V_j||Y_{ij}||Sin(\theta_{ij} - \delta j + \delta j \quad (8.16)$$

The equations (8.15) and (8.16) represent a set of non-linear algebraic equations in terms of voltage magnitude |V| in per unit and δ in radians Afolabi, et, al., (2015). Application of Taylor's series expansion to equations (8.15) and (3.16) about the initial estimate but neglecting all higher order terms, a set of linear equations as described by equation (8.17) can be obtained.

$$[\Delta P_2\ \Delta P_3\ ..\ \Delta P_n\ \Delta Q_2\ \Delta Q_3\ ..\ \Delta Q_n\ ]=$$

$$[\frac{\partial P_2}{\partial e_2}\frac{\partial P_2}{\partial e_3}\cdots\frac{\partial P_2}{\partial e_n}\frac{\partial P_2}{\partial f_2}\frac{\partial P_2}{\partial f_3}\cdots\frac{\partial P_2}{\partial f_n}\ \frac{\partial P_3}{\partial e_2}\frac{\partial P_3}{\partial e_3}\cdots\frac{\partial P_3}{\partial e_n}\frac{\partial P_3}{\partial f_2}\frac{\partial P_3}{\partial f_3}\cdots\frac{\partial P_3}{\partial f_n}\ \ldots\frac{\partial P_n}{\partial e_2}\frac{\partial P_n}{\partial e_3}\cdots\frac{\partial P_n}{\partial e_n}\frac{\partial P_n}{\partial f_2}\frac{\partial P_n}{\partial f_3}\cdots\frac{\partial P_n}{\partial f_n}\ \frac{\partial Q_2}{\partial e_2}\frac{\partial Q_2}{\partial e_3}\cdots\frac{\partial Q_2}{\partial e_n}\frac{\partial Q_2}{\partial f_2}\frac{\partial Q_2}{\partial f_3}\cdots\frac{\partial Q_2}{\partial f_n}\ \frac{\partial Q_3}{\partial e_2}\frac{\partial Q_3}{\partial e_3}\cdots\frac{\partial Q_3}{\partial e_n}\frac{\partial Q_3}{\partial f_2}\frac{\partial Q_3}{\partial f_3}\cdots\frac{\partial Q_3}{\partial f_n}\ ..\frac{\partial Q_n}{\partial e_2}\frac{\partial Q_n}{\partial e_3}\cdots\frac{\partial Q_n}{\partial e_n}\frac{\partial Q_n}{\partial f_2}\frac{\partial Q_n}{\partial f_3}\cdots\frac{\partial Q_n}{\partial f_n}](8.17)$$

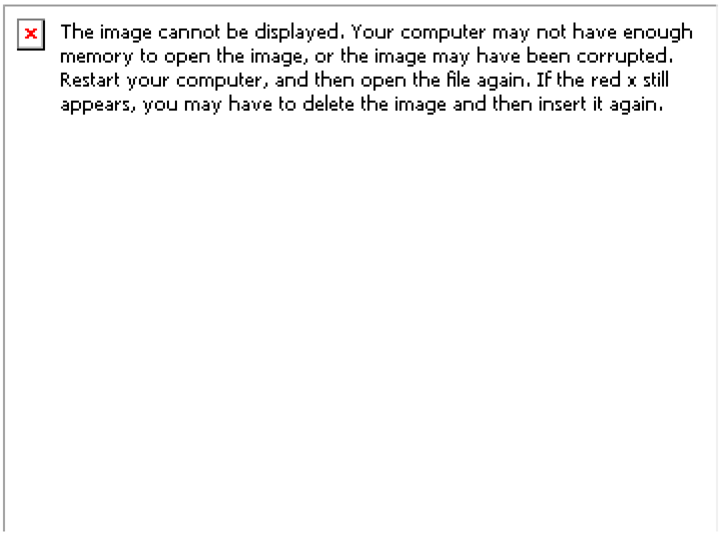

Figure 8.2: Flow chart for load flow solution using Newton-Raphson method (Hadi,2010)

RESULTS AND DISCUSSION

The load flow enhancement problem is solved in the Electrical transient analysis Program (ETAP). The number of iterations in the Electromagnetic analysis algorithm is set to 150. The average running time for one iteration is around 10 s. The total computational time average for 150 iterations is around 25 min. By implementing the simulations and considering the objective functions and constraints of each situation, values of the optimal nominal capacity diesel generators connected to each bus of the Microgrid (MG) without applying the distribution resource protocol (DRP) are shown in Tables 9.3 and 9.6, respectively.

The comprehensive loading capacity as well as the voltage profile of the Calabar power distribution network was obtained using the Electrical Transient Analysis Program (ETAP 16.00) as shown in Table 9.1. It was observed that the voltage magnitude suffered variation from the nominal operating voltage value and angle for both techniques. Thus, the system was then subjected to further analysis to identify the cause of the noticeable variations.. The analysis was extended to load MW, and Load Mvar, Generator MW, and generator Mvar, Loss MW, and Losses Mvar systems.

Table 9.1 General Load Flow Result

Study ID	lf
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	37

Branches	34
Generators	4
Power Grids	1
Loads	9
Load-MW	240.822
Load-Mvar	79.422
Generation-MW	258.704
Generation-Mvar	200.593
Loss-MW	11.881
Loss-Mvar	76.171
Mismatch-MW	0
Mismatch-Mvar	0

The results presented in Table 9.1 indicate 37 bus networks, 34 branches, 4 generators, 1 power grid and 9 divert load, and there is substantial challenge within the electrical distribution system, specifically concerning high losses attributed to both the length of the lines and the poor quality of cables. The cumulative sum of losses, totaling 17,881.4 KW and 12,117.1 *KVAR* respectively, signifies a significant drain on the system's resources. These losses are particularly impactful on transformers T2, T3, and T4 in the upper stream of the network.

Table 9.2 Load Flow Report Before, and After Compensation

Bus ID	Nominal Kv	Voltage Percentage	Operating Voltage KW	Compensated voltage KVAr
Bus 14 (Loading T3)	11	86.8	86.84	0.04
Bus 16	11	86.8	86.84	0.04
Bus 17(Loading T2)	11	86.8	86.84	0.04
Bus 18 (Loading T1)	33	85.1	85.11	0.01
Bus 19 (loading T1)	33	85.1	85.11	0.01
Bus 20	33	89.7	91.13	1.43
Bus 21	33	89.7	91.13	1.43
Bus31	33	85.1	85.11	0.01
Bus 32	11	85.1	85.11	0.01
Bus 55	11	89.5	91.13	1.63
Bus 109	33	91.1	91.13	0.03
Amika	33	67.1	67.13	0.03
Diamond Hill	11	70.8	70.82	0.02
EPZ1-BAO-YAO	33	89.3	89.33	0.03
EPZ2	33	88.7	88.72	0.02
Flour Mill	11	70.8	70.82	0.02
Total Voltage Compensated				6.33%

Table 9.2 above presents the voltage profile of the bus after compensation. This indicates there is improvement in the voltage magnitude of all the buses that previously fell outside the acceptable value limit of 0.95£V£1.05. the total operating voltage percentage of 6.33% was compensated to Flour Mill Bus, EPZ2 bus, EPZ1-BAO-YOA, Diamond Hill bus Amika Bus, Bus 109, Bus 55, Bus 32, Bus 31, Bus 21, Bus 20, Bus 19, Bus 18, Bus 17, Bus 16, Bus 15, and Bus 14, respectively.

The group of buses, including Bus 109, Calabar Main, Akamkpa, Amika Bus, Diamond Hill, EPZ1-BAO-YAO,EPZ1-UNICEM, EPZ2, Flour Mill, Niger Mill Bus, and State Housing exhibits diverse MW loading values. Despite this diversity, the consistent presence of 0 percentage loading implies that these buses are operational but not under significant load. Understanding the reasons behind this commonality is crucial for enhancing overall network efficiency. (Innocent et. al., 2025).

Table 9.3 Losses Summary Report after Compensation

Bus ID	Nominal Kv	Voltage Percentage	Voltage	Voltage losses percentage
BUS 52	11	88.9	86.84	-2.06
BUS 54	11	88.9	86.84	-2.03
AKAMKPA	33	83.7	83.68	-0.02
STATE HOUSING	11	60.2	60.19	-0.01
Total voltage losses percentage				-4.30%

Table 9.3 is a representation of the summary of system losses after compensation. Reduction in the overall system loss was observed from Bus 52 (88.9kw to 86.84), Bus 54 (88.9 kw to 86.84), Akamkpa Bus (83.7 kW to 68.68kW), and State Housing Bus (60.2kW to 60.19kW) for active power loss and from -4.3kW for the reactive power loss

Table 9.4: Cable and line transformers load result for Calabar power distribution network.

ID	Type	kW Flow	kvar Flow	Current (A)	Voltage percentage Loading
Cable1	Cable	13770.3	8534	422.2	
Line2	Line	10684.8	8921	291	
Line3	Line	90881.4	8818.5	1987	
Line4	Line	24236.5	8279.3	2234	
Line7	Line	14029.6	8631.7	1221	
Line8	Line	14029.6	8631.7	1221	
Line9	Line	2888.1	9226.6	187.7	
Line10 EPZ 1- BAO-YAO	Line	26599.1	9200.1	551.2	
Line11	Line	43703.2	9179.4	880.6	
T1	Transf. 2W	124315	87469.1	664.8	253.3
T3	Transf. 2W	59835.2	65972.5	389.6	148.4
T4	Transf. 2W	74553.6	47151.8	385.8	147
T7	Transf. 2W	0	0	0	0

T14	Transf. 2W	0	0	0	0
T15	Transf. 2W	0	0	0	0

Table 9.5; Cable and Line Transformers load result Before and After compensation

ID	Kw Flow	KVar Flow	Amp Flow (A)	Voltage Percentage	Percentage of Voltage Loading
Cable 1 (AMIKA)	130770	8534	17752.4	8524.99	2.2E+07
Line 10 EPZ1-BAO-YAO	26599.1	9200.1	26572.2	9189.99	35762.2
Line 11(EPZ2)	43703.2	9179.4	43658.8	9197.9	52825.9
Line 2(AKAMPKA)	10684.8	8921	10590.4	8911.95	19502.3
Line3 (NIGGER MILL)	90881.6	8818.5	90787	8797.84	99584.8
Line 4 (STATE HOUSING)	24236.5	8279.3	24207.8	8256.06	35463.8
Line 7 (DIAMOND HILL)	14029.6	8631.7	14014.2	8618598	22182.8
Line 8 FLOUR MILL)	14029.6	863.7	1013.87	8618.6	14830.5
Line 9 (EPZ1_UNICEM)	2888.1	9226.6	5885.18	9217.27	15102.4
T1	12431.5	87469.1	12307.2	0.1	12307.3
T3	59835.2	65973.5	-5977.4	65907.5	530.162
T4	74553.6	47151.8	-0.4	47104.6	47104.2

Table 9.6; Lump load result for Calabar distribution network

ID	Rating/Limit	Rated kV	kW	kvar	Amp	% PF	% Loading	V Terminal
Lump1 [AKANKPA LOAD]	14806.8 kVA	33	10684.8	8921	291	76.76	112.3	83.68
Lump1 [AMIKA LOAD]	18200 kVA	33	13770.3	8534	422.2	85	132.6	67.13
Lump1 [NIGER MILLS]	98259.3 kVA	33	90881.4	8818.5	1987	99.53	115.6	80.39
Lump1 [STATE HOUSINGS]	29356.2 kVA	11	24236.5	8279.3	2234	94.63	145	60.19
[DIAMOND LOAD]	18296.1 kVA	11	14029.6	8631.7	1221	85.17	127.1	70.82
[EPZ 1- BAO-YAO LOAD]	29330.2 kVA	33	26599.1	9200.1	551.2	94.51	107.4	89.33
[EPZ 1-UNICEM LOAD]	10046.1 kVA	33	2888.1	9226.6	187.7	29.87	106.8	90.1
[EPZ 2 LOAD]	46642 kVA	33	43703.2	9179.4	880.6	97.86	107.9	88.72
[FLOUR MILL LOAD]	18296.1 kVA	11	14029.6	8631.7	1221	85.17	127.1	70.82

Table 9.7 Lump Load result after compensation

Bus ID	Nominal Kv	Rating/Limit kVA	Voltage %Mag	Operating Voltage KW	Total Compensated Voltage KVAr
LUMP1 [AMIKA LOAD]	33	18200	67.13	67.1	0.03
DIAMONG HILL LOAD)	11	18296.1	70.82	70.2	0.62
EPZ1-BAO-YAO	33	29330.2	89.33	89.3	0,03
EPZ1-UNICEM LOAD	33	10046.1	90.1	90.1	0
EPZ2 LOAD	33	46642	88.72	88.7	0.02
FLOUR MILL LOAD	11	18296.1	70.82	70.8	0.02
Total load compensated					1.62

Table 9.7 Lump load flow losses After Compensation

Bus ID	Nominal KV	Rating/Limit KVA	Voltage %Mag	Voltage KW	Total Losses KVAr
Lump 1[AKPAMKPA Load]	33	14806.6	83.68	83.7	-0.02
LUMP1 [NIGGER MILL]	33	98259.3	80.39	80.4	-0.01
LUMP1 [STATE HOUSING]	11	29356.2	60.19	60.2	-0.01
Total losses after compensated					-0.4

Table 9.8: The Summary of each of the Generator Source

ID	Rating/Limit	Rated kV	MW	Mvar	Amp	% PF	% Generation
Gen1	5 MW	0.415	0	0	0	0	0
Gen3	5 MW	0.415	0	0	0	0	0
Gen4	5 MW	0.415	0	0	0	0	0
Gen5	5 MW	0.415	0	0	0	0	0
U1 MAIN TRANSMISSION LINE	0.132 MVA	132	258.704	200.593	1432	79.03	

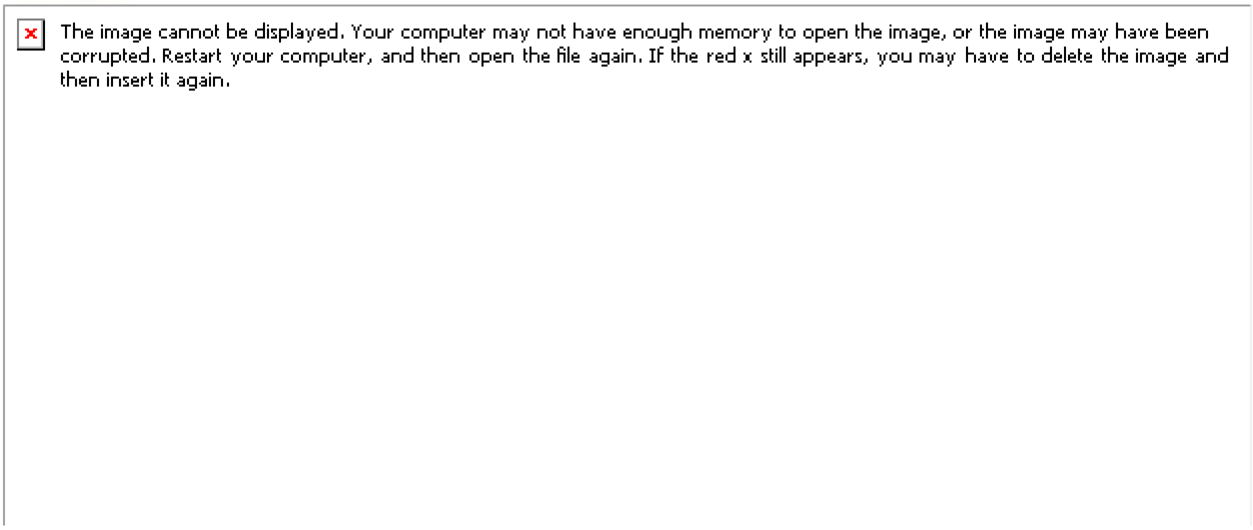

Figure 9.1 **Real power (kW) distribution across major lines/cables**.

CONCLUSION

The results from Tables 9.6, 9.7, and 4.8 clearly demonstrate the impact of compensation on the Calabar distribution network. Before compensation (Table 9.6), most lumped loads operated under stressed conditions, with high percentage loading exceeding 100% in several (e.g., AMIKA 132.6%, State Housing 145%) and low voltage profiles (as low as 60.19%). Power factor variation was also significant, particularly at EPZ1-UNICEM (29.87%), indicating poor reactive power management and system inefficiency. After compensation (Table 9.7), there was noticeable improvement in voltage stability across major buses. Although voltage magnitudes did not drastically increase, they became more stable and closer to acceptable operating ranges, with minor reactive power compensation (total ≈ 1.62 kVAr). This indicates targeted reactive support helped stabilize weak buses such as AMIKA, Diamond Hill, and EPZ feeders. Furthermore, loss analysis after compensation shows a reduction in reactive power losses (total ≈ -0.4 kVAr), suggesting improved network efficiency and reduced system stress, particularly at AKAMPKA, Niger Mill, and State Housing buses. From Table 9.8, generation is primarily supported by the main transmission line (258.704 MW, 200.593 Mvar), while local generators remain inactive, indicating reliance on grid supply.

Overall, compensation improved voltage profiles, reduced losses, and enhanced system stability, though further optimization and distributed generation integration are recommended for better performance.

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