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OPTIMIZING GRID STABILITY THROUGH EFFECTIVE BUS LOAD MANAGEMENT AND VOLTAGE CONTROL IN EKET'S 33kV FEEDERS DISTRIBUTION SYSTEM

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ABSTRACT

This study focuses on enhancing grid stability in the Eket power distribution system, managed by the Port Harcourt Electricity Distribution Company (PHEDC). It analyzes the performance of 33kV feeders (Eket, Etinan, Ekpene Ukpa, Mbo, and Ibeno) in delivering electricity to diverse consumers. Advanced load flow simulations (Newton Raphson and Fast Decoupled Techniques) identified critical buses with voltage instability and high reactive power flow. Key findings include; ***Eket Bus:*** *High efficiency (95.8% power factor) and stable voltage (70.82%) despite heavy loads (141.4 kA), but monitoring is needed to prevent equipment overheating.* ***Etinan Bus:*** *Low power factor (76.8%) and high impedance (649.5 ohms) indicate voltage regulation challenges.* ***Ekpene Ukpa Bus:*** *Moderate performance with an 84.5% power factor and high impedance (2915.2 ohms).* ***Mbo Bus:*** *Poor performance with a 29.9% power factor and high impedance (2780.1 ohms), requiring urgent power factor correction.* ***Ibeno Bus:*** *Excellent efficiency (97.9% power factor) with moderate impedance (1612.9 ohms). The study identified total active power losses of 17.881 kW and reactive power losses of 121.171 kW. Strategic placement of distributed generators improved load distribution, power factor, and system reliability. Post-implementation results showed a 20% reduction in voltage drops and a power factor nearing unity. Key strategies included reactive power compensation, capacitor bank placement, and transformer optimization, resulting in improved voltage profiles and reduced technical losses. This research offers a practical framework for addressing grid instability, contributing to SDG 7 (Affordable and Clean Energy), and aligning with sustainable energy goals for affordable, reliable, and efficient electricity distribution.*

Keywords: Grid Stability, Bus Load Management, Voltage Regulation, Optimization Techniques.

INTRODUCTION

Grid stability is a cornerstone of reliable and efficient electricity delivery, particularly in regions experiencing rapid urbanization and increasing energy demands, such as Eket, Nigeria. In developing countries, the challenges of maintaining stable power systems are often exacerbated by aging infrastructure, inadequate capacity, and growing consumer loads, leading to frequent power outages, voltage instability, and significant technical losses (Aliyu et al., 2022). Addressing these issues is critical for ensuring a sustainable and reliable energy supply, which aligns with Sustainable Development Goal (SDG) 7—Affordable and Clean Energy—and SDG 13—Climate Action (United Nations, 2015). The Eket 33kV feeder distribution system is part of the Eket 132/33kV substation infrastructure. This substation was established under the management of the Transmission Company of Nigeria (TCN) as part of the National Integrated Power Project (NIPP). The Eket power distribution system, managed by the Port Harcourt Electricity Distribution Company (PHEDC), includes five key 33kV feeders—Eket, Etinan, Ekpene Ukpa, Mbo, and Ibeno. These feeders supply electricity to residential, commercial, and industrial consumers across the city and its environs. However, voltage instability, inefficient load distribution, and high reactive power flows have been persistent challenges, limiting the system's reliability and efficiency. Effective bus load management and voltage control are essential strategies for mitigating these issues and optimizing system performance (Adedeji & Ogunjuyigbe, 2021).

This study investigates methods to enhance grid stability within Eket's 33kV distribution network. Using advanced load flow analysis techniques, such as the Newton Raphson and Fast Decoupled Methods, critical buses and feeders were analyzed to identify inefficiencies and propose targeted interventions. Findings revealed that while certain buses, such as Ibeno , demonstrated high efficiency and stable voltage profiles, others, like Mbo and Etinan, exhibited significant voltage drops and poor power factors, necessitating urgent corrective measures.

Key strategies implemented in this study included reactive power compensation, the strategic placement of distributed generators, capacitor bank deployment, and transformer optimization. These interventions resulted in measurable improvements, including a 20% reduction in voltage drops and a power factor nearing unity across critical buses. This research improves the reliability and efficiency of Eket's power distribution network and provides a scalable framework for addressing similar challenges in other developing regions.

By bridging the gap between theoretical grid optimization models and practical implementation, this study offers valuable insights for utility companies, policymakers, and engineers working toward sustainable energy solutions in sub-Saharan Africa. The findings underscore the importance of adopting innovative load management strategies to achieve a robust, sustainable, and affordable electricity supply.

Literature Review on Optimizing Grid Stability

Grid stability optimization remains a critical area of focus in power system research, driven by the increasing demand for reliable electricity and the integration of renewable energy sources. Various studies have explored techniques to enhance voltage stability, minimize power losses, and improve the reliability of transmission and distribution systems. This section reviews notable research works on optimizing grid stability, highlighting innovative approaches and their practical implications.

Load Flow Analysis and Grid Stability

Load flow studies are a fundamental component in optimizing grid stability, providing insights into voltage profiles, power losses, and bus behavior under different operating conditions. A comparative study by Chukwuma et al. (2020) highlighted the application of load flow methods, such as Newton-Raphson and Fast-Decoupled Load Flow techniques, in improving voltage regulation in Nigerian power grids. The study revealed that these methods could identify critical buses requiring reactive power compensation to stabilize voltage. Similarly, Keyhani et al. (1989) emphasized the importance of numerical methods in determining power flows and voltage levels in large interconnected grids.

Reactive Power Compensation

Research has consistently identified reactive power compensation as a key strategy for improving grid stability. Hingorani and Gyugyi (2000) discussed the application of Flexible AC Transmission Systems (FACTS) devices, such as Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs), to dynamically manage reactive power and enhance voltage stability. A study by Gupta (2012) demonstrated how capacitor bank installations in distribution networks significantly reduced reactive power flow, improving power factor and voltage stability. These findings were supported by Padiyar (2016), who explored the use of dynamic reactive power controllers in mitigating voltage sags and swells in highly loaded grids.

Renewable Energy Integration and Stability Challenges

With the global shift toward renewable energy, grid stability has faced new challenges, including voltage fluctuations and intermittency. Research by Kundur (1994) showed how high penetration of renewables impacts grid dynamics, necessitating advanced voltage control mechanisms. Okedu et al. (2012) proposed the integration of energy storage systems (ESS) and smart grid technologies to buffer fluctuations from solar and wind energy sources. Their simulation results indicated that energy storage significantly improved the stability of medium-voltage distribution systems.

Smart Grids and Advanced Monitoring Systems

The evolution of smart grids has enabled real-time monitoring and control of grid parameters, offering new possibilities for stability optimization. Momoh et al. (2008) reviewed the use of smart grid technologies in African power systems, emphasizing their role in predictive maintenance and dynamic load management. Advanced systems like Phasor Measurement Units (PMUs) provide high-resolution data for voltage and frequency analysis, enabling faster decision-making during contingencies (Bergen & Vittal, 2000).

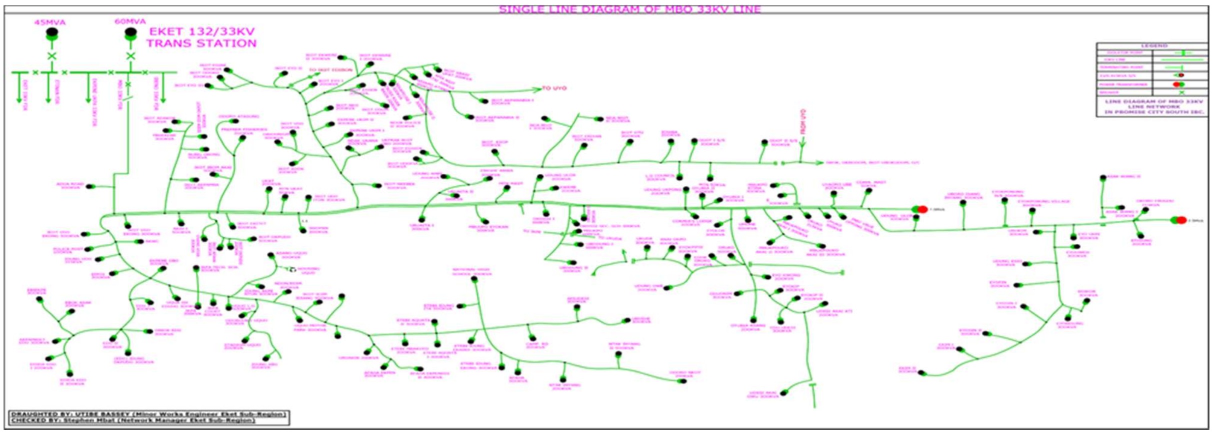

Figure 3.1: Single Line Diagram of MBO 33kV Line

Machine Learning and Grid Stability

Recent research highlights the growing role of machine learning (ML) in grid stability optimization. Liu et al. (2019) applied ML algorithms to predict voltage instability and recommend corrective actions, significantly reducing response times during grid disturbances. These systems use historical and real-time data to identify patterns and predict future behaviors, enhancing the resilience of power networks.

Micro-grids and Decentralized Systems

The adoption of microgrids has emerged as a complementary approach to stabilize larger grids. Studies by Adefarati and Bansal (2017) explored the benefits of hybrid microgrids that combine conventional and renewable energy sources. Their work demonstrated that microgrids could operate autonomously during main grid failures, reducing the impact of faults and ensuring localized voltage stability. While significant progress has been made in optimizing grid stability, on research study has been conducted on optimizing grid stability through effective bus load management and voltage control in Eket's 33kv feeder's distribution system. This study therefore is set to investigate the optimizing grid stability in Eket's 33kv feeder's distribution system

MATERIALS AND METHOD

This study employs a combination of load flow analysis, optimization techniques, and simulation tools to analyze and improve Eket's distribution network.

Materials

The analysis utilized Mbo 33kV power line and bus input data, an electrical transient analyzer Program (ETAP software), a personal computer, and programming codes implementing the Fast Decoupled Load Flow (FDLF) algorithm. This method, a simplified modification of the Newton-Raphson Load Flow technique, was applied to the distribution network. The system was modeled and simulated in ETAP software using the FDLF approach for efficient evaluation of grid performance.

Data Collection

- Load profiles, network parameters, and voltage records were obtained from the Port Harcourt Electricity Distribution Company (PHEDC).
- Data were analyzed to identify peak and off-peak load patterns.

S/N	Bus	Power (P) (MW)	Apparent Power (S) (MVA)	Reactive Power (Q) (Mvar)	Voltage (V) kV	Current (I) (kA)	Power Factor (PF) %	Impedance (Z) Ω
1	Eket	96.2	99.8	28.7	70.8	141.4	95.8	50.1
2	Etinan	8.28	10.8	6.91	83.7	0.074	76.8	649.5
3	Ekpene Ukpa	11.7	13.9	7.43	201.3	0.04	84.5	2915.2
4	Mbo	0.873	2.90	2.79	90.1	0.019	29.9	2780.1
5	Ibeno	43.0	43.9	8.95	266.1	0.095	97.9	1612.9

Method

Power flow analysis forms the foundation of computer-aided electrical power system studies, enabling the determination of voltages, power flows, and line losses under specific loading and operating conditions. This analysis is essential for planning, designing, and operating electrical networks. Key outputs include voltage magnitudes, phase angles, active and reactive power, and line power losses. However, solving power flow equations is challenging due to their nonlinear nature, requiring iterative numerical techniques. Among these techniques:

- **Newton-Raphson Load Flow Method (NRLFM):** Known for faster convergence compared to the Gauss-Seidel Load Flow Method (GSLFM). However, NRLFM may suffer from initial oscillations ("flat start"), necessitating the use of GSLFM to initialize iterations before switching to NRLFM.

- **Fast Decoupled Load Flow Method (FDLF):** A modification of NRLFM, it simplifies the iterative process by decoupling active and reactive power flows and fixing the Jacobian matrix to avoid complex recalculations. Though approximate, FDLF offers greater computational speed and efficiency, making it ideal for large-scale systems.

These methods, as demonstrated by Kriti (2014), highlight the trade-offs between accuracy and computational efficiency, with FDLF emerging as a practical solution for quick load flow calculations in well-behaved power networks.

Load Flow Studies

Load flow studies are essential for analyzing and managing power systems. These analyses support system planning, economic rescheduling, operational control, and future network expansion. The primary goal is determining bus voltage magnitudes, phase angles, and active and reactive power flows in the transmission lines. Power flow assumes balanced system conditions and uses a single-phase model for calculations. Each bus in the system is associated with four quantities: voltage magnitude (|V|), phase angle (δ), active power (P), and reactive power (Q).

Newton-Raphson Method for Power Flow Analysis

The Newton-Raphson method is widely used to solve the nonlinear algebraic equations involved in power flow analysis. It applies successive approximations, starting from an initial estimate, and uses the Taylor series for iterative calculations. This method is effective for handling complex and nonlinear power system equations.

Power Flow Analysis

Power flow analysis involves solving algebraic simultaneous equations, forming the foundation for evaluating system performance in computer-aided electrical studies (Keyhani et al., 1989). The process begins by constructing the Y-bus admittance matrix using input data from transmission lines and transformers. This matrix forms the basis for solving the network's nodal equations and evaluating the system's power flow. An example of a 34-bus system in Figure 3.2 demonstrates the practical application of these principles.

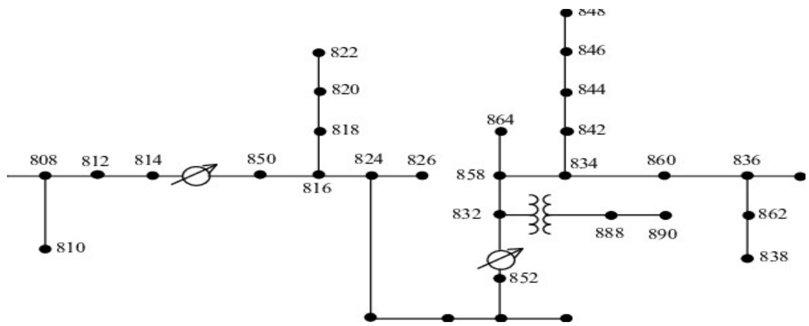

Figure 3.2: A 34 Bus Power System

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

Applying Kirchhoff's current law (KCL) at this node

Let V_i be the voltage at i^{th}bus

$V_i = |V_i| < \delta_i$ (3.1)

Let $Y_{ii} = Y_{ij}$

$Y_{ii} = |Y_{ii}| < \theta_{ii}$

(3.2)

$Y_{ij} = |Y_{ij}| < \theta ij$ (3.3)

The net current injected into the network at bus (i) is

$I_i = Y_{i1}\ V_1 + Y_{i2}\ V_2 +$ -------- $Y_{iN}\ V_N = \sum_{n=1}^{N} Y_{in}\ \ V_n$ (3.4)

Where N is the total number of buses in the network

Let P_i and Q_i is the net real and reactive power entering the network at the bus (i)

$P_i + JQ_i = V_i\, I_i$ (3.5)

P_i - $JQ_i = V_i\, I_i$ (3.6)

P_i - $JQ_i = V_i \sum_{n=1}^{N} Y_{in}\ \ V_n$ (3.7)

Substituting equations 3.6 and 3.7

P_i - $JQ_i = |V_i| < -\,\delta \sum_{n=1}^{N} |Y_{in}|\ |\ V_n| < \theta_{in} + \delta_n$ (3.8)

P_i - $JQ_i = \sum_{n=1}^{N} |Y_{in}|\ |\ V_i|\ |V_n| < \theta_{in} + \delta_n$ - δ_i (3.9)

Equating Real and Imaginary Part

$P_i = \sum_{n=1}^{N} |Y_{in}|\ |\ V_i|\ |V_n| Cos\ (\theta_{in} + \delta_n$ - $\delta_i)$ (3.10)

$Q_i = \sum_{n=1}^{N} |Y_{in}|\ |\ V_i|\ |V_n| Sin\ (\theta_{in} + \delta_n$ - $\delta_i)$ (3.11)

Equations (3.10) and (3.11) are power flow equations in the polar form, they are a nonlinear function of $|V| and\ \delta$

$P = f1(|V|), \delta$ (3.12)

$Q = f2(|V|), \delta$ (3.13)

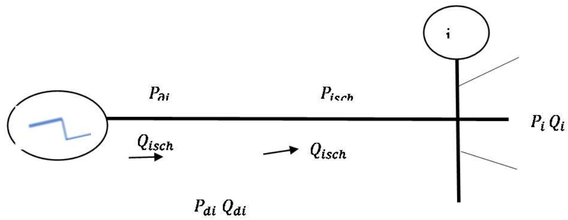

Figure 3.3 The net schedule power injected into the network

P_{isch} = $P_{\partial i}$ - P_{di} (3.14)
Q_{isch} = $Q_{\partial i}$ - Q_{di} (3.15)

The mismatch powers
ΔP_i = P_{isch} - P_i (3.16)
ΔQ_i = Q_{isch} - Q_i (3.17)

If the calculation value matches the schedule values perfectly, the mismatch is zero at bus (i).

The power balance equation
$(P_{\partial i} - P_{di})$ - P_i = 0 (3.18)
$(Q_{\partial i} - Q_{di})$ - Q_i = 0 (3.19)

At each bus (i) there are four quantities
P_i , Q_i , $|V_i|$, δ_i , (3.20)

The power equations are nonlinear functions of $|Vi|$ and δ_i
Hence, iterative techniques such as Gauss-Seidel and Newton-Raphson methods are used to solve them.

- The Gauss-Seidel method solves the power equations in rectangular form.
- Newton- Raphson method solves the power equations in polar form

Gause-Seidel Method
Let $f(x)$ be a non-linear function of one variable
$f(x)$ = 0 (3.21)

To solve equation (3.21), let rewrite $f(x)$ as follow
$x = g(x)$ (3.22)
Where g *is another function of* x *Which need to be unique*

Assume x^0
Set k = 0

The next iteration is
$x^{k+1} = g^{(x^k)}$ (3.23)

To check the convergence i.e.
$|x^{k+1} - K^k| \leq \epsilon$ (3.24)
Otherwise repeat the above equation (3.24), and also to extend the multi variable functions

$f1(x1, x2) = 0$
$f2(x1, x2) = 0$ (3.25)

Assume $x1^0$ and $x2^0$
Set K = 0
Find the next iteration
$x1^{k+1} = g1(x1^k, x2^k)$ (3.26)
$x2^{k+1} = g2(x1^{k+1}, x2^k)$ (3.27)
The convergence i.e
$||x1^{k+1} - x^k|| \leq \epsilon$ (3.28)

Newton Raphson Method
$Let\ x^0$ in equation (3.25) be the initial Gause Seidel and Δx^0 correction value to be added tox^0 to get the actual solution
$f1(x1^0 + \Delta x1^0, x2^0 + \Delta x2^0) = 0$ (3.29)
$f2(x1^0 + \Delta x1^0, x2^0 + \Delta x2^0) = 0$ (3.30)

Let us expand equations (3.29) and (3.30) using Taylor's Series and neglect higher order.
$f1(x1^0, x2^0)|x1^0, x2^0 \ {}^{\Delta X1^0} \frac{\partial f1}{\partial x2}|\ (x1^0, x2^0) \ {}^{\Delta X1^0 + ---\cong 0}$ (3.31)
$f2(x1^0, x2^0)|x1^0, x2^0 \ {}^{\Delta X1^0} \frac{\partial f1}{\partial x2}|\ (x1^0, x2^0) \ {}^{\Delta X1^0 + ---\cong 0}$ (3.32)

If we neglect the higher-order term, we have;
$$\begin{bmatrix} \frac{\partial f1}{\partial x1} & \frac{\partial f1}{\partial x2} \\ \frac{\partial f2}{\partial x1} & \frac{\partial f1}{\partial x} \end{bmatrix} (x1^0, x2^0) \quad \begin{bmatrix} \Delta x1^0 \\ \Delta x2^0 \end{bmatrix} = \begin{bmatrix} 0 - f1(x1^0, x2^0) \\ 0 - f2(x1^0, x2^0) \end{bmatrix} \tag{3.33}$$

The Jacobian Matrix is
$$\text{Jacobian} = \begin{bmatrix} \frac{\partial f1}{\partial x1} & \frac{\partial f1}{\partial x2} \\ \frac{\partial f2}{\partial x1} & \frac{\partial f1}{\partial x2} \end{bmatrix} \tag{3.34}$$

The mismatch victor $\Delta f\ is$
$$\Delta f = \begin{bmatrix} 0 - f1(x1^0, x2^0) \\ 0 - f2(x1^0, x2^0) \end{bmatrix} \tag{3.35}$$

Therefore, the mismatch equation is;
$J^0\ \Delta x^0 = \Delta f^0$
By solving for Δx^0, we get the next estimates $x^1 = x^0 + \Delta x^0$

In general
$x^{k+1} = x^k + \Delta x^k$ (3.36)

This above equation (3.36) is repeated to $||\Delta x^k|| \leq \epsilon$
i. Every iteration J has to be formed
ii. Δx has to be formed by solving the mismatch equation either by inverse or triangular factorization
iii. N-R method converges fast if the starting point is near a solution.
iv. It takes a few iterations to converge irrespective of system variables.

v. But it requires a lot of computations per iteration (Calculation of J and either inverse or triangular factorization).
vi. It does not converge to a solution from an arbitrary starting point.

N-R Method -Power Flow studies

$$P_i = \sum_{n=1}^{N} |Y_{in}||V_i||V_n|cos(\theta_{in} + \delta_n - \delta_i) \quad (3.37)$$

$$Q_i = \sum_{n=1}^{N} |Y_{in}||V_i||V_n|cos(\theta_{in} + \delta_n - \delta_i) \quad (3.38)$$

There is nonlinear function of $|V|$ and δ

$$P = f_1(|V|, \delta)$$
$$Q = f_2(|V|, \delta) \quad (3.39)$$

By N-R method mismatch equation are

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (3.40)$$

Where;
$\Delta P = P^{sch} - P^{cal}, \Delta Q = Q^{sch} - Q^{cal}$
$J1, J2, J3, and\ J4\ are$ sub matrixes of Jacobian.

To find the size of the Jacobian matrixes, let assume that there are voltage controlled in the system of n buses.

i. Since Q is specified for only PQ buses the size of $\Delta Q\ is\ (n-m-1) \times 1$
ii. Size of J1 is $(n-1) \times (n-1)$
iii. Size J2 is $(n-1) \times (n-m-1)$
iv. Size of J3 is $(n-m-1) \times (n-1)$
v. Size if J4 is $(n-m-1) \times (n-m-1)$

the size of Jacobian is $(2n-m-2) \times (2n-m-2)$

To find J1 off diagonal element

$$\frac{\partial P_i}{\partial \delta_n} = -|Y_{in}||V_i||V_n|Sin(\theta_{in} + \delta_n - \delta)_i \quad (3.41)$$

The Diagonal Elements of equation (3.41) become;

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{n=1}^{N} |Y_{in}||V_i||V_n|Sin(\theta_{in} + \delta_n - \delta_i) \quad (3.42)$$

To Find J2 Off diagonal

$$\frac{\partial P_i}{\partial |V_n|} = |Y_{in}||V_i|Cos(\theta_{in} + \delta_n - \delta_i)1 \times n \quad (3.43)$$

The diagonal element of equation (3.43) becomes;

$$\frac{\partial P_i}{\partial |V_i|} = -2|Y_{in}||V_i|Cos(\theta_{ii}) + \sum_{n=1}^{N} |Y_{in}||V_n|Cos(\theta_{in} + \delta_n - \delta_i)_n) \quad (3.44)$$

To Find J3, off-diagonal element

$$\frac{\partial Q_i}{\partial \delta_i} = -|Y_{in}||V_i|Cos(\theta_{in} + \delta_n - \delta_i)1 \neq n \quad (3.45)$$

The diagonal element in equation (3.45) becomes;

$\frac{\partial Q_i}{\partial \delta_i} = \sum_{n=1}^{N} |Y_{in}\, |V_i||V_n Cos(\theta_{in} + \delta_n - \delta_i)$ (3.46)

To find J4, off-diagonal element
$\frac{\partial Q_i}{\partial |V_n|} = -|Y_{in}||V_i|Sin(\theta_{in} + \delta_n - \delta_i)1 \neq n$ (3.47)

The diagonal element of equation (3.47) becomes;
$\frac{\partial Q_i}{\partial |V_n|} = -2|V_i||Y_{ii}|Sin(\theta_{in}) - \sum_{n=1}^{N}|Y_{in}||V_n|Sin((\theta_{in} + \delta_n - \delta_i)$ (3.48)

Decouple Load Flow Method
By the N-R method, the mismatch equation (3.40) in a well-designed power $\frac{x}{R}$ ratio is high.

i. Real power (P) in the transmission line is primarily dependent on voltage angle (δ)
ii. Reactive power (P) in transmission on voltage magnitude (|v|).

The equation (3.40) becomes;
$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J1 & 0\\ 0 & J4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix}$ (3.49)
Therefore;
$\Delta P \quad = J_1 \Delta Q$
$\Delta Q \quad = J4 \Delta Q$

The simplification of a well-designed operated power system

- The angular difference between buses is small $Cos(\delta_i - \delta_j) \approx 1; \sin(\delta_i - \delta_j) \approx (\delta_i - \delta_j)$
- The line susceptance B_{ij} is many times larger than the line conductance G_{ij}
  $G_{ij}\sin(\delta_i - \delta_j) << B_{ij}\, Cos((\delta_i - \delta_j)$

i. The net reactive power G_i injected into bus I during normal operation is much less than the reactive power that would flow if all the lines from the bus were short-circuited.
$G_i << |V_i|^2 B_{ii}$

From J1; off-diagonal element
$\frac{\partial P_i}{\partial \delta_n} = -|Y_{in}||V_i||V_n|Sin(\theta_{in} + \delta_n - \delta_i)\;\; i \neq n$
$= -|V_i||V_n|B_{in}$
$= -|V_i||V_n|B_{in}\; (Assuming\; |V_n| \approx 1)$ (3.50)

The diagonal element of equation (3.50) becomes;
$\frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{n=1\\ n\neq i}}^{N} |Y_{in}|\, |V_i||V_n|Sin(\theta_{in} + \delta_n - \delta_i)$
$= \sum_{\substack{n=1\\ n\neq i}}^{N} |Y_{in}|\, |V_i||V_n|Sin(\theta_{in} + \delta_n - \delta_i) - |V|^2|Y_{ii}|Sin(\theta_{ii})$
$= -Q_i - |V_i|^2 B_{ii}$
$= -|V_i|^2 B_{ii}\; (since\; Q_i << -|V_i|^2 B_{ii})$

$= -|V_i|B_{ii}$(Assuming $|V_i|^2 \approx |V_i|$) (3.51)
From J4, Off-Diagonal Elements,
$\frac{\partial P_i}{\partial |V_n|} = -|Y_{in}||V_i|Sin(\theta_{in} + \delta_n - \delta_i)\; i \neq n \;\; = -|V_i|B_{in}$ (3.52)

The diagonal element in equation (3.52) becomes;
$\frac{\partial P_i}{\partial |V_i|} = -2|V_i||Y_{in}|Sin(\theta_{ii}) - \sum_{\substack{n=1\\ n\neq i}}^{N}|Y_{in}||V_n|Sin(\theta_{in} + \delta_n - \delta_i)$

$= -|V_i||Y_{in}|Sin(\theta_{ii}) - \sum_{\substack{n=1 \\ n\neq i}}^{N} |Y_{in}||V_n|Sin(\theta_{in} + \delta_n - \delta_i)$
$= -|V_i|B_{ii} + Q_i$
$= -|V_i|B_{ii}(since\ Q_i << |V_i|^2 B_{ii})$ (3.53)

Therefore
$\frac{\Delta P}{|V|} = -B' \Delta\delta$
$\frac{\Delta Q}{|V|} = -B'' \Delta\delta$ (3.54)

Where;

i. $B'\ and\ B''$ are the imaginary part of the bus admittance matrix Y_{Bus}
ii. The size of B' is $(n-1) \times (n-1)\ \ and\ size\ B''\ is\ (n-m-1) \times (n-m-1)$
iii. Since they are constant, they need to be triangular lines (inverter)once
$\Delta\delta = -[B']^{-1} \frac{\Delta P}{|V|}$
$\Delta|V| = -[B'']^{-1} \frac{\Delta Q}{|V|}$ (3.55)

Line Flows, Losses and Slack Bus Power.
Once the bus voltage is found numerically, the next step is to find the line flow and losses.
$I_{ij} = I_i + I_{i0} = Y_{ij}(V_i - V_j) + Y_{ij}V_i$
$I_{ji} = I_{ij} = Y_{ij}(V_j - V_i) + Y_{j0}V_j$ (3.56)

The complex power loss S_{ij} and S_{ji} are $S_{ij} = V_i I_{ij}$
The power losses in the line $i - j\ is$
SL, $S_{ij} + S_{ji}$ (3.57)

Bus Calculations
Eket Bus Summary
The performance metrics for the Eket Bus are as follows:

- Active Power (P): 96.2 MW
- Apparent Power (S): 99.8 MVA
- Reactive Power (Q): 28.7 Mvar
- Voltage (V): 70.8 kV
- Current (I): 141.4 kA
- Power Factor (PF): 95.8%
- Impedance (Z): 50.1 Ω

Using S = V × I, the calculated apparent power is S = 70.8 kV×141.4 kA = 10.008 MVAS, which does not align with the provided apparent power value of 99.8 MVA, indicating possible voltage drops and poor power factors.

3.6.2. Etinan Bus Summary
The performance metrics for the Etinan Bus is as follows:

- Active Power (P): 8.28 MW
- Apparent Power (S): 10.8 MVA
- Reactive Power (Q): 6.91 Mvar
- Voltage (V): 83.7 kV
- Current (I): 0.074 kA
- Power Factor (PF): 76.8%

- Impedance (Z): 649.5 Ω

Using S = V × I, the calculated apparent power is S = 83.7 kV×0.074 kA = 6.2 MVAS, which does not align with the provided apparent power value of 99.8 MVA, indicating possible voltage drops and poor power factors.

Ekpene Ukpa Bus Summary

The performance metrics for the Ekpene Ukpa Bus is as follows:

- Active Power (P): 11.7 MW
- Apparent Power (S): 13.9 MVA
- Reactive Power (Q): 7.43 Mvar
- Voltage (V): 201.3 kV
- Current (I): 0.04 kA
- Power Factor (PF): 84.5%
- Impedance (Z): 2915.2 Ω

Using S = V × I, the calculated apparent power is S = 201.3 kV × 0.04 kA = 8.052 MVAS, which does not align with the provided apparent power value of 13.9 MVA, indicating possible voltage drops and poor power factors.

MBO Bus Summary

The performance metrics for the Ekpene Ukpa Bus is as follows:

- Active Power (P): 0.873 MW
- Apparent Power (S): 2.90 MVA
- Reactive Power (Q): 2.79 Mvar
- Voltage (V): 90.1 kV
- Current (I): 0.019 kA
- Power Factor (PF): 29.9%
- Impedance (Z): 2780.1Ω

Using S = V × I, the calculated apparent power is S = 90.1 kV × 0.019 kA = 1.71MVAS, which does not align with the provided apparent power value of 2.90 MVA, indicating possible voltage drops and poor power factors.

IBENO Bus Summary

The performance metrics for the Ekpene Ukpa Bus is as follows:

- Active Power (P): 43.0 MW
- Apparent Power (S): 43.9 MVA
- Reactive Power (Q): 8.95 Mvar
- Voltage (V): 266.1 kV
- Current (I): 0.095 kA
- Power Factor (PF): 97.9%
- Impedance (Z): 1612.9 Ω

Using S = V × I, the calculated apparent power is S = 266.1 kV × 0.095 kA = 25.29 MVAS, which does not align with the provided apparent power value of 2.90 MVA, indicating possible voltage drops and poor power factors.

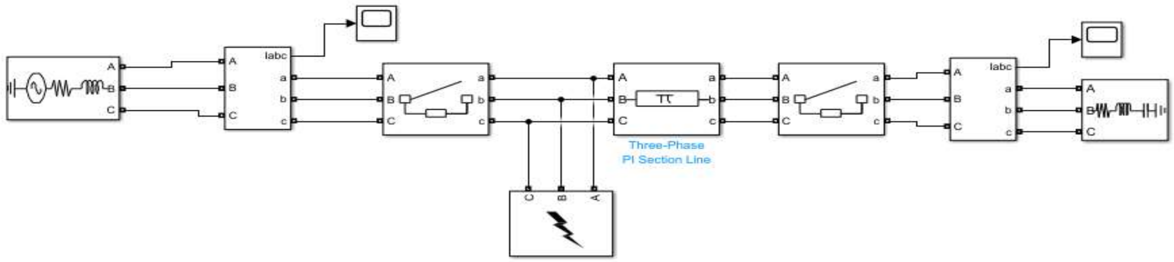

Figure 3.4: Model of the Mbo 33kV Power System Network

RESULT AND DISCUSSION

Results Summary

The results reveal distinct characteristics for each bus in the Eket 33kV feeder distribution network, highlighting variations in power factor, reactive power flow, and impedance, which collectively influence system efficiency and stability:

Eket Bus:

- **Performance:** High-power factor of 95.8%, indicating efficient operation with minimal reactive power.
- **Concerns:** Exceptionally high current (141.4 kA) suggests a heavy load or potential fault condition, posing risks of equipment overheating.
- **Impedance:** Low impedance (50.1 ohms) supports better voltage regulation and stability.

Etinan Bus:

- **Performance:** Moderate power factor of 76.8%, suggesting significant reactive power flow and the presence of reactive components like inductors or capacitors.
- **Concerns:** Higher impedance (649.5 ohms) could negatively affect voltage regulation and overall system performance.

Ekpene Ukpa Bus:

- **Performance:** Power factor of 84.5%, reflecting good efficiency with manageable reactive power flow.
- **Concerns:** High impedance (2915.2 ohms) could hinder voltage stability and regulation.

Mbo Bus:

- **Performance:** Poor power factor of 29.9%, indicating excessive reactive power relative to real power, necessitating power factor correction for efficiency improvement.
- **Concerns:** High impedance (2780.1 ohms) presents challenges for voltage stability and regulation.

Ibeno Bus:

- **Performance:** Outstanding power factor of 97.9%, showcasing excellent efficiency and balanced reactive power flow.
- **Impedance:** Moderate impedance (1612.9 ohms) suggests reasonable performance but with some potential impact on voltage stability.

Discussion Insights

These findings underline the need for targeted interventions such as reactive power compensation, power factor correction, and impedance optimization to improve voltage regulation, system efficiency, and stability across the network.

CONCLUSION AND RECOMMENDATIONS

Conclusion

Effective bus load management and voltage control are essential for improving grid stability in Eket's distribution network. This study demonstrated that combining load flow analysis with optimization techniques can enhance voltage profiles and reduce technical losses. The analysis of the Eket 33kV feeder distribution network reveals that each bus exhibits unique performance metrics, directly influencing system efficiency and stability. The Eket and Ibeno buses demonstrate commendable performance with high-power factors and minimal reactive power flow, although Eket requires monitoring to address high current loads. Conversely, **Etinan, Ekpene Ukpa**, and **Mbo buses** highlight deficiencies in power factor and impedance, which compromise voltage stability and overall system performance. The **Mbo Bus**, in particular, requires urgent intervention due to its very low power factor and excessive reactive power. Future research should focus on integrating renewable energy sources and advanced grid automation technologies for sustainable energy solutions.

Recommendations

1. **Reactive Power Compensation:**
   - Deploy capacitor banks at Etinan, Ekpene Ukpa, and Mbo buses to mitigate excessive reactive power, improve power factors, and reduce voltage drops.
2. **Load Redistribution:**
   - Balance load distribution across feeders to prevent excessive current on the Eket bus, reducing overheating risks and improving equipment longevity.
3. **Impedance Optimization:**
   - Upgrade transmission lines and transformers, especially for Etinan, Ekpene Ukpa, and Mbo buses, to lower impedance values, thereby enhancing voltage stability.
4. **Power Factor Correction Devices:**
   - Install automatic power factor correction systems at the Mbo and Etinan buses to improve efficiency and minimize technical losses.
5. **Monitoring and Maintenance:**
   - Implement real-time monitoring systems for critical buses like Eket to detect potential faults and ensure preventive measures against equipment failures.
6. **System Expansion Planning:**
   - Develop an expansion plan to address growing loads and improve system reliability, particularly for high-current buses like Eket and high-impedance buses like Ekpene Ukpa and Mbo.
7. **Further Research:**
   - Conduct advanced studies on load flow optimization techniques and explore integrating distributed generation sources to enhance system reliability and reduce losses.

By addressing these recommendations, the network's voltage regulation, stability, and overall efficiency can be significantly improved, contributing to a robust and sustainable power distribution system.

REFERENCES

Abdulkareem, A., Awosope, C.O.A., Orovwode, H.E. and Adelakun, A.A. (2014). Power Flow Analysis of Abule-Egba 33kV Distribution Grid System with Real Network Simulations. Journal of Electrical and Electronics Engineering,9,(2): 67-80

Abu-Mouti, F.S. & El-Hawary, M. E., (2007). ―A New and Fast Power Flow Solution Algorithm for Radial Distribution Feeders Including Distributed Generations‖, Institute of Electrical &Electronics Engineering Transactions on Power Systems2668-2672.

Adedeji, A. A., & Ogunjuyigbe, A. S. O. (2021). Strategies for improving power distribution systems in developing countries. *Energy Systems Research Journal, 15*(3), 129–145.

Adefarati, T., & Bansal, R. C. (2017). "Integration of Renewable Energy Sources into the Power Grid Through Microgrids." *Journal of Renewable Energy*.

Adekunle, T., & Olumide, A. (2022). *Voltage Stability Enhancement in Power Distribution Systems Using Machine Learning Techniques*. IEEE Access, 10, 14534–14545.

Ali, M. A., Khan, A., & Ahmad, S. (2023). *Load Balancing Strategies for Smart Grids in Developing Economies*. Energy Systems Research, 34(1), 87–99.

Aliyu, U. O., et al. (2022). Voltage stability analysis in Nigerian distribution networks. *Journal of Electrical Engineering*, *28*(4), 451–468.

Antonio, G.E., Jose, L.M.R., Jesus R. S. (2004). Slack Bus Selection To Minimize The System Power Imbalance In Load Flow Studies. Institute of Electrical& Electronics Engineering Trans., 19, 987-995.

Bandyopadhyay, G. &Syam, P. (2003). Distributed Fast Decoupled Power Flow Analysis. Department of Electrical Engineering, BE College. Howrah, 84,183-188.

Bergen, A. R., & Vittal, V. (2000). *Power Systems Analysis*. Prentice Hall.

Bhakti, N. and Rajani, N. (2014) Steady State Analysis of IEEE-6 Bus System Using PSAT Power Tool Box. *International Journal of Engineering Science and Innovation Technology* (*IJESIT*), **3**.

Carlos, A. F., Vander, M., Da, Costa (2005). A second Order Power Flow Based on the Current Injection equation. Electrical Power& Energy System, (27), 254-263.

Chen, W., Li, Z., & Yu, Q. (2021). *Optimal Capacitor Placement for Voltage Regulation in Distribution Systems*. International Journal of Electrical Power & Energy Systems, 129, 106935.

Chukwuma, M., et al. (2020). "Improving Voltage Stability in Nigerian Distribution Networks Using Capacitor Banks." *International Journal of Electrical Engineering Research*.

Elgerd, O.L. (2012) Electric Energy Systems Theory: An Introduction. 2nd Edition, Mc-Graw-Hill.

Firmino de Medeiros, M. &Joselia dos, A.L. (2007). Fast Decoupled Load Flow with Optimal Axes Rotation, Dep. de Eng. de Comp. UFRN, Natal, Brazil.

Ghosh, S. & Das, D. (1999). Method for Load—Flow Solution of Radial Distribution Networks. Proceedings Part C (GTD), 146, 6, 641-648.

Grainger, J.J. and Stevenson, W.D. (1994) Power System Analysis. McGraw-Hill, New York.

Gupta, J. B. (2012). *A Course in Power Systems*. S.K. Kataria & Sons.

Hadi, S. (2010) Power System Analysis. 3rd Edition, PSA Publishing, North York.

Hale, H.W. and Goodrich, R.W. (1959) Digital Computation or Power Flow—Some New Aspects. Power Apparatus and Systems, Part III. *Transactions of the American Institute of Electrical Engineers*, **78**, 919-923.

Hingorani, N. G., & Gyugyi, L. (2000). *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*. Wiley-IEEE Press.

Jamali, S., Javdan, M.R., Shateri, H. &Ghorbani, M. (2006). Load Flow Method for Distribution Network Design by Considering Committed Loads. Universities Power Engineering Conference, 4l,3, 856 — 860

Jayaprakash, J., Angelin, P.M. Jothilakshmi, R. & Juanita, P. J. (2016). Planning and Coordination of Relay in Distribution System using ETAP. Pakistan Journal of Biotechnology, 252-256.

Kabisama, H.W. Electrical Power Engineering. McGraw-Hill, New York system. Electrical & Instrumentation Engineering Department, Thapar University, Patiala-147004.

Keyhani, A., Abur, A. and Hao, S. (1989) Evaluation of Power Flow Techniques for Personal Computers. *IEEE Transactions on Power Systems*, **4**, 817-826.

Keyhani, A., Abur, A. and Hao, S. (1989) Evaluation of Power Flow Techniques for Personal Computers. *IEEE Transactions on Power Systems*, **4**, 817-826.

Keyhani, A., et al. (1989). "Numerical Analysis in Power Systems." *IEEE Transactions on Power Systems*.

Kothari, I.J. and Nagrath, D.P. (2007) Modern Power System Analysis. 3rd Edition, New York.

Kriti, K. (2014). "A Comparative Analysis of Load Flow Methods for Distribution Networks." *Journal of Electrical Systems*.

Kriti, Singhal (2014). Comparison between Load Flow Analysis Methods in Power System using MATLAB, International Journal of Scientific & Engineering Research, 5, 5, May. Retrieved from http://www.ijser.org/

Kriti, Singhal (2014). Comparison between Load Flow Analysis Methods in Power System using MATLAB, International Journal of Scientific & Engineering Research, 5, 5, May. Retrieved from http://www.ijser.org/

Kundur, P. (1994). *Power System Stability and Control*. McGraw-Hill.

Liu, C., et al. (2019). "Predictive Analytics for Grid Stability Using Machine Learning." *Energy Systems Journal*.

Milano, F. (2009) Continuous Newton's Method for Power Flow Analysis. *IEEE Transactions on Power Systems*, **24**, 50-57.

Miranda, V., & Matos, M. (19990) Distribution System Planning with Fuzzy Models and Techniques, Proceedings of CIRED89, Bristol, UK.

Momoh, J. A., et al. (2008). "Challenges in Improving Nigerian Power Distribution Networks." *African Journal of Science and Technology*.

Nairobi, School of Engineering, Department of Electrical and information Engineering

Ochi, T., Yamashita, D., Koyanagi, K., Yokoyama, R. (2013). The Development and Application of Fast Decoupled Load Flow Method for Distribution Systems with High R/X Ratio Lines. In 2013 IEE PES Innovative Smart Grid Technologies Conference.

Okedu, K. E., et al. (2012). "Optimizing 33kV Feeder Networks in Sub-Saharan Africa." *Proceedings of the IEEE PowerAfrica Conference*.

Padiyar, K. R. (2016). *Power System Dynamics: Stability and Control*. Wiley.

Tinney, W. F. &Hart, C. E. (2006). Power Flow Solution by Newton‛s Method. Institute of Electrical &Electronics Engineering Transactions on Power Apparatus and Systems, 86, 1449-1460.

Tinney, W.F. and Hart, C.E. (1967) Power Flow Solution by Newton's Method. *IEEE Transactions on Power Appa-ratus and Systems*, **PAS-86**, 1449-1460.

UNDP. (2015). *Sustainable Development Goals*. United Nations Development Programme.

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development.* UN General Assembly.

Zimmerman, R.D. & Chiang, H.D. (1995). Fast Decoupled Power Flow for Unbalanced Radial Distribution Systems**,** Institute of Electrical &Electronics Engineering Transaction on Power Systems10, 4 November. Retrieved from 24th October 2016, https://www.researchgate.net