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Determination of five (5) Predictive Analyzers for the Mitigation of voltage and Power Outages Using Stability Index

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Abstract
This research on 'Evaluation of five (5) Predictive Analyzers for Mitigation of voltage collapse Using Voltage Stability Index'is timely. The researcher employs Q-V modal analysis to predict voltage instability in the existing south-south/south-east 330Kv grid network. The application of NEPLAN 555 software package was used in the modelling of the south-south 330KV grid system. The violation of the simulated network was compensated using static var compensator (SVC) for improving deviation of loading margin of the buses close to the point of voltage collapse. This method was used because of the direct relation of the node voltage and reactive power changes which plays significant role in the analysis of voltage stability, the node voltage and reactive power change are also related to eigenvalues that give more accurate result for determining participation factors, this account for the prediction of weak buses that may consequently leads to voltage instability. The existing 330Kv grid consist of seven (7) generating station, twenty (20) transmission lines and eleven (11) load buses. The most critical node is identified by the least eigenvalues and from the selection once least eigenvalues are identified, they are evidently recommended as weak node for probable solution. Following the criteria of ranking as contained in table 4.2, which shows critical buses of the network exhibited higher participation factor particularly, bus-12 (New-heaven) followed by bus-18 (Ugwaji). These buses are selected as candidate buses targeted for intervention that required reactive power support for enhance system stability and prevent voltage collapse. Essentially, these buses are selected criteria and ranked as candidate's buses targeted for probable consideration in order to avoid system outages. Similarly, the Nigeria 330KV grid, 48 buses were also modelled using electrical transient analysers program (ETAP 19.0.1) on the view to assess the evaluation of five (5) predictive analyser for the examination of system operating condition for immediate remedial action. This 330Kv grid 48-buses provided the flexibility for the assessment and evaluation of five (5) predictive-indexes, including fast voltage stability index (FVSI), line stability index (LMN), line stability factor (LQP), Voltage stability index (LD) and novel line stability index (NLSI) are presented to predict the proximity of the line close to voltage collapse. These voltage stability indices are based on active and reactive power injection into the network configuration for system evaluation and performance measurement. The five (5) predictive indices actually examined and evaluated prediction of line voltage profile for the 330Kv transmission network, 48-buses. This study particularly engaged twenty-four (24) cases for each analysis of FVSI, LMN, LQP, LD and NLSI respectively which are graphically as contained in figure 4. Which show the predictive pattern, evidently, three (3) of the five (5) predictive indices including NLSI, LMN, and FVSI captured and investigated the predictive behaviour as line close to instability while the other two (2) (LQP, LD) do not have good predictive capacity for system collapse. That is LD and LQP are very slow to the prediction of system collapse. Qualitatively, in the case of line 1, the predictive value of the indices is: FVSI (0.895), LMN (0.89456), NLSI (1.04077.35) while LQP and LD are: (0.002975 and 0.00151002) this means that LQP and LD has slower property for the predictions of the line voltage instability order investigation. Consequently, the Nigerian 330Kv integrated power system is currently consisting of existing network, national independent power project (NIPP), and independent power producer (IPP). It contained generation stations, transmission line and buses. This complex network is highly challenging on daily basis to be attended to and given serious attention in the event of the unlikely to ensure quick restoration to allow the grid to gain synchronism to avoid system collapse using the study case as research-tool to enhanced reliable power supply.
***Keywords: Voltage Stability Indices, Reactive Power Compensation, Transmission Line, Voltage Collapse, Power Factor Correction**.*

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I. INTRODUCTION

Historically, the exact date that electricity was invented wasn't documented (Nenritmwa and Gotodok, 2022), so many efforts have been made to understand the accurate time and place that electricity was first generated in the world till date haven't yielded any result. It is, therefore, safe to say that electricity started in time immemorial. Before electricity came to be what we have now and use, various scientists played different yet complementary roles in the materialization of electricity, in 1752 Benjamin Franklin's famous kite experiment became the break-out moment for electricity cognizance. In 1831, British scientist Michael Faraday's discovery of basic principles of electricity generation is one of the major milestones in the evolution of electricity.

The Nigerian electricity industry started in 1896 with the commissioning of Ijora Power Plant. The Electricity Corporation of Nigeria (ECN) was set up in 1951 for electricity distribution, while the Niger Dams Authority (NDA) was set up in 1961 for power generation and transmission (Uzoma, 2020)... ECN and NDA were merged in 1972 to form the vertically integrated NEPA responsible for power generation, transmission, distribution and marketing throughout Nigeria. Major power generation for grid connection started in 1961. Between 1961 and 1990, total grid connected generation capacity grew to about 6,200MW, with over 10,000Km route length of transmission lines. Due to un-sustained investments and inefficiency in network and plant operations,

- ❖ Generation capability fell persistently and reached as low as below 2,000MW
- ❖ There was large scale transmission and distribution bottlenecks.

Due to graft and overbearing government interferences, and inefficiency in the Distribution arm of the sector – the customers' satisfaction remained low and revenue collection was very poor. The low revenue collection affected investment capability of the industry; the viscous cycle continued. At the onset of the civilian administration in 1999, the Nigerian electric power sector had reached, perhaps, the lowest point in its 100 years history. Of the 79 generation units in the country, only 19 units were operationally reliable. Average daily generation was about 1,750 MW. No new power infrastructure was built between 1990 - 1999. The newest plant was completed in 1990 and the last major transmission line built in 1987. An estimated 90 million people were without access to grid electricity. Accurate and reliable estimates of industry losses were unavailable, but were believed to be in excess of 40%. Based on the dismal state of the power sector, due to lack of investments, the government decided to embark on a power policy, which recommended reform of the sector.

In this era of increasing dependency on electricity, it is very important to have a constant, uninterrupted system (Niki, 2010). The cost to the society of a major power outage could be in billions of dollars. The present-day power supply is more complex than ever before and hence its operation in an economic and secure fashion offers the engineer formidable problems. Among these problems is maintaining a stable voltage profile to avoid loss of stability and voltage collapse.

Electricity power supply is the necessity required for the development of micro and macro-economic activities on daily basis. This study will look at the evaluation for the mitigation of voltage collapse in the Nigeria power system using predictive voltage collapse indices. The scope is limited to 20-buses Nigeria network using NEPLAN-tool and 48-buses system Nigeria 330KV power network using-Etap tool.

There are obvious challenges of real time integration of the existing computational techniques in real power transmission especially in the context of the national grids, it is very necessary to analyze systems situation where simulations are transformed into real time network before eventually collapse occurs.

Thus, this research study, will close the gaps on the view to address the prevailing circumstance in the system condition as:

(i) To reduce uncontrollable load capacity that may over stressed the power system that may result, into voltage collapse.

(ii) To match generating capacity to the consumer load demand to avoid system violations.

1.1 Aim of the Research Work

To improve the mitigation of voltage collapse in the Nigeria power system using voltage stability indices (fast voltage stability index, (FVSI), line stability index (LMN), Line stability factor (LQP), voltage stability index (LD), and novel line stability index (NLSI))

1.2 Objectives of this Research

Power system stability and control are critical aspects for reliable operations of power grid, this means to achieve this goal, the following objectives are considered:

(i) To determine the voltage stability limits of the existing Nigeria 330KV and 132KV, using five (5) predictive analyzers (FVSI, LMN, LQP, LD and NLSI)

(ii) To determine voltage instability that may results into system collapse.

(iii) Comparison evaluation for five (5) predictive analyzers (FVSI, LMN, LQP, LD and NLSI).

(iv) To evaluate voltage collapse scenarios and probable mitigation measures for the south-south, south-east 330KV grid network (using NEPLAN).

This study will essentially, consider the determination of the stability conditions of the existing state (stable, unstable or critical) that may results into voltage collapse or outages, on the view to engage participation factor tool as criteria for identification of weak or strong buses as candidate buses to be attended to for either remedial or immediate action in the event of the unlikely similarly, five (5) predictive indices are also included in the study case to determine the line/ voltage stability limit for the maximum power transfer capability as major consideration for this research work..

Also, this research work shall provide adequate information for future planning, expansion or upgrade of 33KV H31 Apo feeder network. It will also determine the steady state operational values as the losses along the branches of the network. Finally, the current findings regarding to the results are required to make recommendations on the solution for system improvement and expansion of the network configuration under investigation.

II. LITERATURE REVIEW

Power system stability and control are critical aspects of ensuring the reliable operation of power grids. Over the years, various methods and techniques have been developed to maintain the stability of the power system. In this literature review, we will summarize some of the recent research on power system stability and control.

Muyeen *et al.* (2014) on their research, focuses on the importance of power system stability and the need for enhancing it using hybrid renewable energy sources and hybrid control techniques. It provides a comprehensive review of the existing research on the topic, highlighting the advantages and limitations of different techniques. The book discusses the use of various renewable energy sources, including wind, solar, and hydro, and their integration into the power system. It also examines the use of hybrid control techniques, which involve combining different control strategies to enhance power system stability. It concludes that the use of hybrid renewable energy sources and hybrid control techniques can significantly improve power system stability, reduce greenhouse gas emissions, and increase the reliability of the power system. However, they note that further research is needed to optimize the integration of renewable energy sources into the power system and to develop more effective control strategies. Overall, it provides a valuable review of the current state of research on power system stability enhancement using hybrid renewable energy sources and hybrid control techniques.

Omorogiuwa (2019), the Nigerian 330Kv transmission network is faced with various problems. It focused on the technical and non-technical losses estimated in the network. The network is characterized by high voltage drops and power losses which can be attributed to low generation, long and fragile radial network, making it highly prone to failure, unreliability, inefficiency and poor performance. The network was analyzed using Power World Simulator (PWS), the result showed that the energy loss due to the 330Kv transmission network is about 454.73 GW amounting to over 4.4 billion naira.

Jena *et al.* (2015). The paper titled "A Review of Power System Stability Enhancement Using Hybrid Renewable Energy Sources and H∞ Controller". Provides a comprehensive review of the use of Hybrid Renewable Energy Sources and H∞ Controller (HRES-H∞) for power system stability enhancement. The paper discusses the importance of power system stability and the need for efficient and effective control techniques to maintain it. The authors provide a detailed review of the various types of HRES-H∞ and their applications in power systems. They highlight the advantages and limitations of different HRES-H∞ techniques and provide insights into their ability to manage the variability and uncertainty of renewable energy sources. The authors also examine the challenges associated with the integration of HRES-H∞ into the power system, including the impact of intermittent renewable energy sources on power system stability and the need for advanced control strategies to manage them. They provide a detailed analysis of the existing literature on the topic, highlighting the key findings and recommendations. The paper concludes that HRES-H∞ can significantly enhance power system stability, reduce greenhouse gas emissions, and increase the reliability of the power system. However, the authors note that further research is needed to optimize the integration of HRES-H∞ into the power system and to develop more effective control strategies. Overall, the paper provides a valuable review of the current state of research on power system stability enhancement using HRES-H∞. It highlights the importance of developing advanced control strategies to manage the variability and uncertainty of renewable energy sources and to maintain power system stability in the face of changing energy.

Andrej *et al*, (2014). Transient stability and steady-state (small signal) stability in power girds are reviewed. Transient stability concepts are illustrated with simple examples; in particular, we consider three methods for computing region of attractions: time-simulations, extended Lyapunov function, and sum of squares optimization method. We discuss steady state stability in power systems, and present an example of a feedback control via a communication network for the 10 Unit 39 Bus New England Test system.

Akinloye*et al*. (2016). The term voltage collapse is often used in place of system collapse. It is the process by which the series of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system. The cause of this can be categorized into two; technical and non-technical. The technical causes may be due to tripping of lines on account of faulty equipment or increase in load than the available supply. The data comprising the series of system collapse experienced by the Nigeria power system since 1987 to 2014 were presented and analyzed to view the frequency of the occurrence of the collapse. Also, suggestions were given on the ways to reduce the incidence of system collapse on the power system.

Airoboman *et al*. (2015). Assesses the trends in voltage instability in the Nigerian Power System Network (PSN). Data of voltage instability were collected for the year (1995-2013) and was analyzed sequentially using simple statistics and the result interpreted graphically. The result shows an average collapse of 5.1% recorded during this period. 50.8%of the voltage collapses are as a result of total grid collapse while 48.4% collapses are as a result of partial grid collapse while 0.9% collapses caused by foreign objects. The paper therefore emphasizes how poor government policies had led to poor power generation hence leading to voltage instability in the Nigeria power system network.

Carson *et al*. (1993). Voltage stability is a major concern in the planning and operation of electric power systems. This book provides a clear, in-depth explanation of voltage stability, covering both transient and longer-term phenomena and presenting proven solutions to instability problems. They describe equipment characteristics for transmission, generation, and distribution/load subsystems of a power system, together with methods for the modelling of equipment. Readers will find static and dynamic computer simulation examples for small equivalent power systems and for a very large power system, plus an account of voltage stability associated with HVDC links. They will also get helpful planning and operating guidelines, computer methods for power flow and dynamic simulation, and descriptions of actual voltage instability incidents.

Almeida *et al*. (2017). The objective is to describe a process which was developed in the Portuguese TSO (REN – Rede Electrica Nacional, SA) whose main purpose is to identify voltage collapse situations without the need for the specific EMS module. The process is based on the power flow module of PSS/E software from Siemens Power Transmission Distribution, Inc., running automatically through an application developed in Python, which performs an SV analysis. Its results are available via browser from control room PC's and are updated every 30 minutes, allowing to monitor the system security levels and to take suitable remedial actions to prevent a voltage collapse situation. The need to develop a process to identify voltage collapse situations in the Portuguese Transmission System arose with voltage problems identified in a specific substation when performing N-l contingency analysis. The operator training simulator, an important tool to analyze and understand the power system behavior, was also used to study and demonstrate the voltage collapse phenomenon.

Hasani*et al*. (2005). Different analysis methods have been used for voltage stability assessment. In comparison with static analysis methods, little work has been done on dynamic analysis of large interconnected power systems. Voltage instability can be studied effectively with a combination of static approaches and time simulations. This paper discusses voltage stability assessment using mixed static and dynamic techniques. Using static methods, a voltage stability based ranking is carried out to specify faint buses, generators and links in power system. The system is analyzed for most severe conditions. Then, time domain simulation is performed for the conditions determined by voltage instability ranking. The mixed approach benefits from advantages of both static and dynamic analyses. The New England (IEEE 39 bus) system was used as a test system.

Olajiga *et al.* (2018). This paper presents a critical review of the current national electricity grid in Nigeria, how voltage stability is maintained in the grid, find out the limitations of the transmission network and compare the different options for overcoming them in the available literature, learn from the previous studies about the use of renewable energy sources in Nigeria, understand the prospect of developing electricity grid in Nigeria by learning about the identified challenges from literary sources.

III. MATERIALS AND METHODS

3.1 Materials Used

The materials used for this research were collected from Transmission Company of Nigerian (TCN) with focus on South-South/South-East 330kV grid network. The materials collected includes;

(i) Bus data consisting of available generating capacity in MW for seven (7) generators and eleven (11) load buses in the South-South/South-East 330kV grid network.

(ii) Line data consisting of nine (9) single circuit, nine (9) double circuit, one (1) triple circuit and one (1) quadruple circuit.

(iii) Static Var compensator used for improving the loading margin of the buses close to the point of voltage collapse

(iv) NEPLAN 555 software package was used for modeling the South-South/South-East 330kV grid network.

(v) Etap version (19.0.1) was used for modeling the single line diagram of 48 bus, 330KV Nigeria grid system Nigeria system.

3.2 Method Used

(i) To collate numerical dataset from existing 330KV and 130kv Nigeria network.

(ii) To formulate governing equations for the study case under investigation.

(iii) To model the existing study case in a single line diagram using NEplan software (20 buses) and ETAp-software application tool for 48- Buses.

Q-V modal analysis with predictive indices as (FVSI, LMN, LQP, LD, and NLSI), were used to predict voltage instability in the existing South-South/South-East 330kV grid network, the techniques used considered:
(i)The node voltage and reactive power change are directly related and plays a significant role in voltage stability analysis.
(ii)The node voltage and reactive power change are related to eigenvalues which gives more accurate result for determining the participation factors
(iii)The participation factor plays a useful role in the prediction of weak buses or nodes with high voltage instability.

Table 3.1: Bus Data

Bus Information			Load Data			Generation	
Bus No	**Name**	**Type**	**MW**	**MVar**	**B-Shunt**	**MW_{Instal}**	**MW_{Aval}**
1	Adiabor TS	PQ	140	90	-75Mvar	-	-
2	Afam GS	Slack	-	-	-	1376	800
3	Aladja TS	PQ	100	70	-	-	-
4	Alaoji GS	PV	-	-	-	450	126
5	Alaoji TS	PQ	400	150	-	-	-
6	Asaba TS	PQ	185.7	169.5	-	-	-
7	Azura GS	PV	-	-	-	450	300
8	Benin TS	PQ	383	150	-150Mvar	-	-
9	Delta GS	PV	-	-	-	900	620
10	Ikot-Abasi TS	PQ	146	85	-	-	-
11	Ikot-Ekpene TS	PQ	321	160	-	-	-
12	New Heaven TS	PQ	180	130	-	-	-
13	Odukpani GS	PV	-	-	-	565	226
14	Okpai GS	PV	-	-	-	450	300
15	Onitsha TS	PQ	184	134	-75Mvar	-	-
16	Onne TS	PQ	80	50	-	-	-
17	Sapele GS	PV	-	-	-	1020	120
18	Ugwaji TS	PQ	230	115	-	-	-

Source: Transmission Company of Nigeria, TCN

3.6 Modal Analysis Method of Voltage Stability

The modal analysis is an effective analytical technique used to predict voltage instability in large power system networks. It basically depends on the values of eigenvalue and eigenvector obtained from reduced Jacobian matrix obtained from the conventional Newton-Raphson power flow solution. Power system in recent time, has improved in terms of size and complexity and the conventional Newton-Raphson method fails to converge in multiple contingencies, due to the singularity of the Jacobian matrix at the point of maximum loading because any change in the modal reactive power will cause an infinite change in the modal voltage and the system will collapse. Therefore, to mitigate the challenge of Jacobian matrix singularity, the power flow equation is modified by reducing the Jacobian matrix to linearize its dimension.

1) Determination of Reduced Jacobian Matrix

The first step in the modal analysis technique is the determination of the reduced Jacobian Matrix (Jr) which is obtained from the Newton Raphson power flow method by putting the value of $\Delta P = 0$, in the conventional Newton-Raphson method then solving (3.1) simultaneously to eliminate the angle part we have

$0 = J_{11}\Delta\theta + J_{12}\Delta V$ (3.1)

$\Delta Q = J_{21}\Delta\theta + J_{22}\Delta V$ (3.2)

From (3.2) making $\Delta\theta$ subject of the equation we have

$\Delta Q = [-J_{21}J_{11}^{-1}\Delta V]$ (3.3)

Substituting (3.3) into (3.2)

$\Delta Q = J_{21}[-J_{21}J_{11}^{-1}\Delta V] + J_{22}\Delta V$ (3.4)

$\Delta Q = \Delta V[J_{22} - J_{21} - J_{11}^{-1}J_{12}]$ (3.5)

$J_R = [J_{22} - J_{21} - J_{11}^{-1}J_{12}]$ (3.6)

$\Delta Q = J_R\Delta V$ (3.7)

$\Delta V = J_R^{-1}\Delta Q$ (3.8)

The matrix Jr represent the linearized relation between the incremental changes in bus voltage
ΔV and reactive power injection ΔQ. It's well known that, the system voltage is affected by both real and reactive power variations.

2) Determination of the Most Critical Mode

The second step in modal analysis is the determination of the most critical mode. The eigenvalues of the Jacobian matrix (**J_R**) can be used to determine the modes of the power network. The least eigenvalue of the reduced Jacobian matrix (J_R) determines the most critical mode of the power system. The mode indicates the system nearness to voltage instability. Once the least eigenvalue is identified, the rest are ignored because they are considered to be strong enough modes.

$J_R = \lambda\phi\xi$ (3.9)

$I_R^{-1} = \lambda^{-1}\phi\xi$ (3.10)

Where

ϕ: right eigenvector matrix of J_R

ξ: left eigenvector matrix of J_R

λ: diagonal eigenvalue matrix of J_R

Substituting (3.10) into (3.8)

$\Delta V = \lambda^{-1}\phi\xi\Delta Q$ (3.11)

$\Delta V = \frac{\phi_i\xi_i}{\lambda_i}\Delta Q$ (3.12)

$\phi_i\xi_i = 1$ (3.13)

$\Delta V = \frac{1}{\lambda_i}\Delta Q$ (3.14)

(i) If all eigenvalues are positive, the system is voltage stable because the i^{th} mode voltage and i^{th} reactive power change are in the same direction.

(ii) If at least one of the eigenvalues is negative, the system is voltage unstable because the i^{th}mode voltage and i^{th} reactive power change are in opposite direction.

(iii) If eigenvalues become zero, the system will collapse because any change in the modal reactive power will cause an infinite change in the modal voltage

3) Determination of Bus Participation Factor

The last process of the modal analysis is the determination of the participation factors for load buses. The factor is an indicator the close proximity of a particular bus to voltage instability and is calculated for bus that has the most critical mode.

$P_{ki} = \xi_i\eta_i$ (3.15)

Where

ξ_i: column right eigenvector matrix of J_R

η_i: row left eigenvalue matrix of J_R

Substituting (3.15) into (3.14)

$\Delta Q = J_{21}[-J_{21}J_{11}^{-1}\Delta V] + J_{22}\Delta V$ (3.16)

$\Delta Q = \Delta V[J_{22} - J_{21} - J_{11}^{-1}J_{12}]$ (3.17)

$J_R = [J_{22} - J_{21} - J_{11}^{-1}J_{12}]$ (3.18)

$\Delta Q = J_R\Delta V$ (3.19)

$\Delta V = J_R^{-1}\Delta Q$ (3.20)

The matrix Jr represent the linearized relation between the incremental changes in bus voltage ΔV and reactive power injection ΔQ. It's well known that, the system voltage is affected by both real and reactive power variations.

4) Determination of Bus Participation Factor

The last process of the modal analysis is the determination of the participation factors for load buses. The factor is an indicator the close proximity of a particular bus to voltage instability and is calculated for bus that has the most critical mode.

$P_{ki} = \xi_i\eta_i$ (3.21)

Where

ξ_i: column right eigenvector matrix of J_R

η_i: row left eigenvalue matrix of J_R

3.7 Optimization Technique used for Reactive Power Compensation

Optimization is the act of obtaining the best results under given circumstances. The ultimate goal of all such decisions is either to minimize the effort required or to maximize the desired benefit. There are various optimization techniques used for reactive power compensation. For this thesis, static var placement is the optimization techniques for reactive power compensation. However, its placement may impact negatively on the system if not optimally placed and sized.

$SVC = \frac{Q_{load} - Q_{gen}}{1 - \left(\frac{V_{min}}{V_{ref}}\right)^2} * \left(\frac{\Delta V}{V_{ref}}\right)$ (3.22)

Where
Q_{load}: reactive power demand of load in Mvar
Q_{gen}: reactive power generated by other sources in the system
V_{min}: minimum allowable voltage in p.u
V_{ref}: reference voltage in p.u
V_{ref}: voltage deviation from reference in p.u

3.8 Load Flow Equation and Method of Solution

Complex power injected into an *ith*bus of a power system is given as:
$S_i = P_i + jQ_i = V_i I_i^* \; i = 1,2,$ (3.23)
Where V_i is the voltage at the *ith*bus with respect to ground and $I_i^*$is the complex conjugate of source current I_i injected into the bus. Since it is more convenient to work with$I_i$rather than I_i^*in load flow problems, the complex conjugate of the above equation is given as:
$S_i^* = P_i + jQ_i = V_i^* I_i$ (3.24)

But $I_i = \sum_{k=1}^{n} Y_{ik} V_k$ (3.25)

Thus$S_i^* = P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k \; i = 1,2, \ldots n$ (3.26)

In Polar form
$V_i = |V_i| < \delta_{i,} V_i^* = |V_i| < -\delta_i$
$V_k = |V_k| < \delta_{k,} V_{ik}^* = |V_{ik}| < -\theta_{ik}$` (3.27)

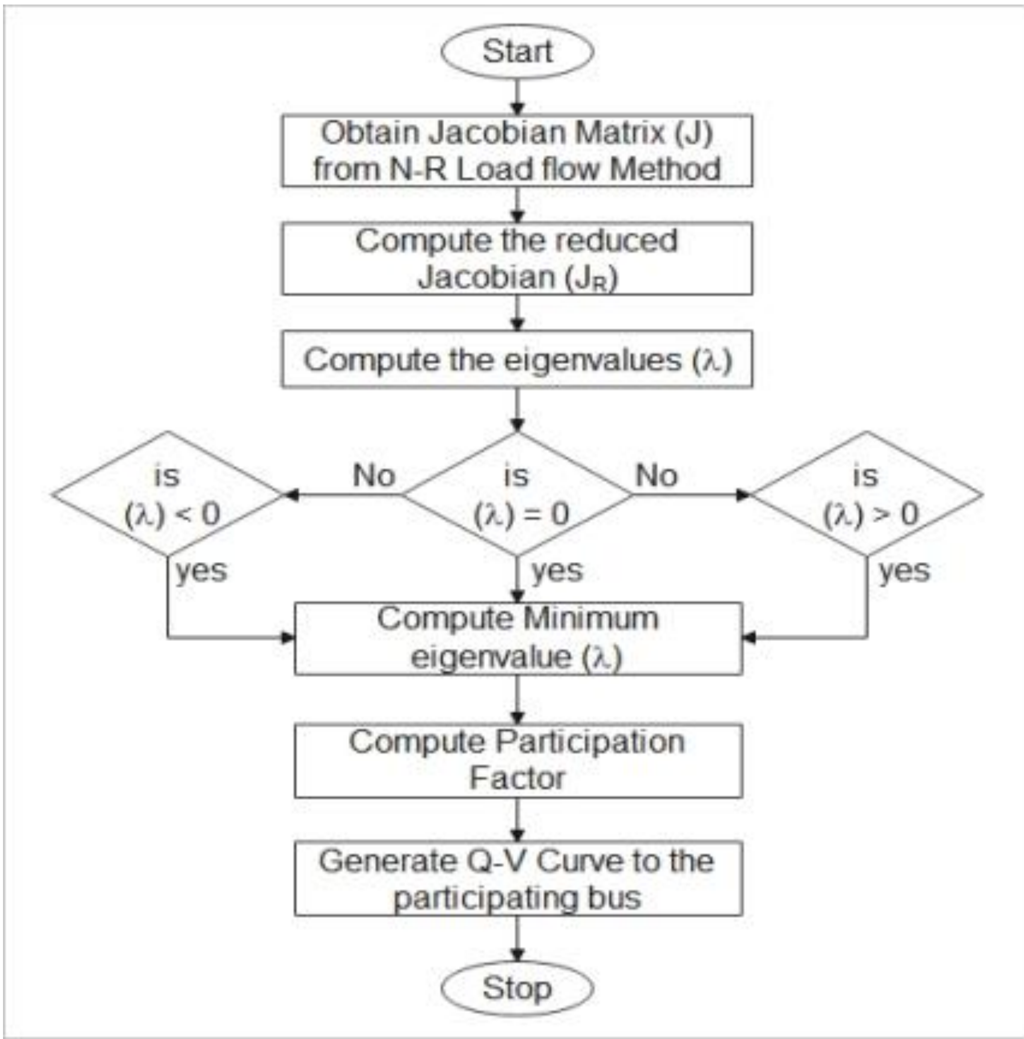

Figure 3.1: Flowchart for Bus Participation Factor

Real Power, $P_i = |V_i| \sum_{k=1}^{n} |Y_{ik}||V_k|$

$cos(\theta_{ik} + \delta_{k,} - \delta_i)$ (3.28)

Reactive power, $P_i = |V_i| \sum_{k=1}^{n} |Y_{ik}||V_k|$

$sin(\theta_{ik} + \delta_{k,} - \delta_i)$ (3.29)

These equations are non-linear and can only be solved via numerical solution.

3.9 Power System Line Parameters

3.9.1 Per-Kilometre Active Resistance *(R)*

$R_0 = \frac{1000\,\ell}{A}(\Omega/\text{km})$ (3.30)

Where ℓ is the design resistivity of conductor *(Q,m)*

A is the cross-sectional area of conductor *(m²)*

3.9.2 Per-Kilometre Inductive Reactance (Non-stranded conductor)

$x_0 = 0.445\left(\frac{D_{GMD}}{r}\right) + 0.0157(\Omega/\text{km})$ (3.31)

Where *r* is the conductor radius

D_{GMD} is the geometric mean distance between phase conductors.

3.9.3 Per-Kilometre Capacitive Susceptance b_o

$b_0 = \frac{7.58}{Log\left(\frac{D_{GMD}}{r}\right)}(1/\Omega/\text{km})$ (3.32)

3.9.4 Geometric Mean Distance

For a single Circuit

$D_{GMD} = \sqrt[3]{D_{RB}D_{YR}D_{BY}}$ (3.33)

Where *D* is the spacing between the conductors.

For overhead conductors arranged horizontally

$$\left\{\begin{aligned} D_{GMD} &= \sqrt[3]{2D^3} \\ &= \sqrt[3]{2} \\ &= 1.26D \end{aligned}\right\}$$ (3.34)

3.10 Percentage Load analysis on Feeder

mz

Where Active Power (P_D) on feeder

$= \frac{\text{Average Current on Feeder}}{60} \times 100$ (3.35)

3.11 Complex Load on Distribution Transformers

Complex load demand =Transformer Capacity × Percentage Loading on transformer

Where percentage loading on transformer

$=\frac{I_R+I_Y+I_n}{3I_n} \times 100$ (3.36)

3.12 Voltage Drop (V_D)

$V_D = V_s - V_r$ (3.37)

Where V_s= *Sending end Voltage*

V_r = Receiving end Voltage

And $V = IZ$ (3.38)

Thus, $V_D = V_s - V_r = IZ$ (3.39)

Where I= Average Current on Feeder

Z = Impedance of feeder

Therefore, percentage voltage drops

$=\frac{V_D}{V_s} \times 100$ (3.40)

3.13 Transformer Tap Changing

The principle of regulating the secondary voltage is based on changing, the number of turns on the primary or secondary in changing the transformation ratio are presented as,

$= \frac{V_2}{V_1} = \frac{N_2}{N_1} = K$ (3.41)

$= V_2 = \frac{V_1 N_2}{N_1} = E_1 K$ (3.42)

Where K = transformation ratio
V_1= primary voltage
V_2 = secondary voltage

Decrease in primary turns causes increase in emf per turn, and so in secondary output voltage. Secondary output voltage can also be increased by increasing secondary turns and keeping primary turns fixed.

3.14 Shunt Capacitors for Compensation

Shunt capacitors are installed near load terminals to provide leading Volt-Ampere-Reactive (VAR) and thus to reduce the line current. Hence, by using shunt capacitors, line drop is reduced, and voltage profile is improved. Shunt capacitors are switched in when capacity demand on the distribution system rises and voltage of the buses drop.

Assume a load is supplied with a real power P, lagging reactive Power, Qi and apparent power, Si at a lagging power factor.

Thus,

$S_1 = (P_1^2 + Q_1^2)^{\frac{1}{2}}$ (3.43)

When a Shunt Capacitor of Q_cKVar is installed at the load, the apparent power can be reduced from S_1 to S_2.

$S_2 = (P^2 + Q_2^2)^{\frac{1}{2}}$ (3.44)

Similarly,

$S_2 = (P^2 + (Q_1 - Q_c)^2)^{\frac{1}{2}}$ (3.45)

Since current is directly proportional to power, (i.e. IαS), automatically, reduction in the apparent power leads to reduced current flow. In turn line drop is reduced and voltage profile improved.

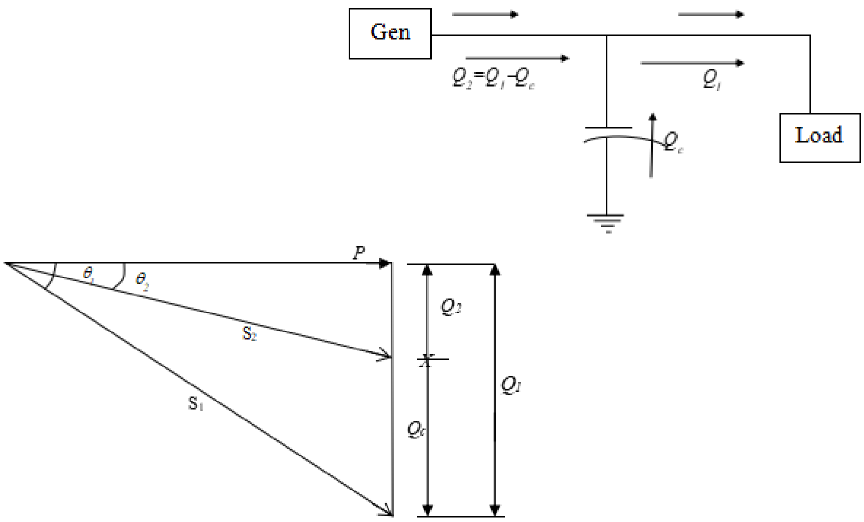

Figure 3.2: Pythagoras theorem for capacitor compensation (capacitor bank)

3.15 Power Factor Correction

If P is the real power supplied, Q is the lagging reactive power and S is the apparent power at a lagging power factor. Then,

$\cos\theta_1 = \left(\frac{P}{S_1}\right)$ (3.46)

and

$\cos\theta_1 = \frac{P}{(P^2+Q_1^2)^{\frac{1}{2}}}$ (3.47)

When a shunt capacitor supplying reactive power of $Q_c$is applied, the new reactive power $Q_2$of the system will be $Q_2, = Q_1 - Q_c$. (3.48)

Hence, power factor becomes;

Th $\cos\theta_2$

$= \frac{P}{(P^2+Q_1^2)^{\frac{1}{2}}}$ (3.49)

and

$\cos\theta_2 = \frac{P}{(P^2+Q_1-Q_c)^{\frac{1}{2}}}$ (3.50)

3.16 Objective Function of Optimal Capacitor Placement (OCP)

The objective of OCP is to minimize the cost of the system. This cost is measured in four ways:

(i) Fixed capacitor installation cost
(ii) Capacitor purchase cost
(iii) Capacitor bank operating cost (maintenance and depreciation)
(iv) Cost of real power losses.

Mathematically, cost can be represented as:

$$Min\ objective\ function\ \sum_{i=1}^{N_{bus}}\left(xC_{0i}+Q_{ci}C_{1i}+B_iC_{2i}T\right)+C_2\sum_{i=1}^{N_{bus}}\left(T_1P_L^1\right)$$ (3.51)

Where N_{bus}:Number of bus candidates
X_i:0/1, 0 means no capacitor installed at bus i
C_{0i} :Installation cost
C_{1i} : Per Kvar cost of capacitor banks
Q_{ci} : Capacitor bank size in Kvar
B_i: Number of capacitor banks
C_{2i} :Operating cost of per bank, per year
T: Planning period (years)
C_2: Cost of each KWh loss, in $/KWh
l: Load levels, maximum, average and minimum
T_1: Time duration, in hours, of load level
P_L^1 ; Total system loss at load level

3.17 Modal Analysis

The modal (eigenvalue) analysis can be used essentially as a formidable analytical tool to investigate both proximity and mechanism of voltage instability (Subramani *et al.,*2019). The process of voltage collapse is a dynamic occurrence, but static power network solution methods can still be utilized to generate criteria which are good markers of voltage stability margin and can ascertain weak buses of the system.

Modal analysis method is capable of calculating voltage collapse or instability in power system networks, the major aspect of this technique involves the estimation of the smallest eigenvalues and related eigenvectors of the reduced Jacobian matrix acquired from performing load flow analysis. Eigenvalues have a-great deal of relationship with the mode of voltage and reactive power variation, and are employed to estimate voltage instability in a power network system (Yari & Khoshkhoo, 2017). After execution of modal analysis, the participation factors are usually utilized to easily identify the weakest connections or buses in the system. The participation factor values can adequately be, used to determine the weakest bus in the system. The participation factor values are usually obtained from the eigen-vectors analysis of eigenvalues.

By solving linearized power flow equation. The DP and DQ matrix I s obtained

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix}$$ (3.52)

Considering .PA = 0, the reduced Jacobian matrix obtained in equation 2.65 is expressed as:

$\Delta J_L = [J_4 - J_3J_1^{-1}J_3]$ (3.53)

$\Delta Q = J_L\Delta V$ (3.54)

$\Delta V = J_1^{-1}\Delta Q$ (3.55)

Putting

$J_L = \xi\wedge\eta$ (3.56)

where
ξ, is right eigenvector matrix
his left eigenvector matrix
Dis diagonal eigenvalue matrix
Then, inverting equation 3.56 produces

$J_L^{-1} = \xi \wedge^1 \eta$ (3.57)

And substituting equation 3.57 in equation 3.56 given as;

$\Delta V = \xi \wedge^1 \eta \, \Delta Q$ (3.58)

and

$\Delta V = \Sigma_i \frac{\xi_i \eta_i}{\delta_i} \Delta Q$ (3.59)

Where η_i is the i[th] row of the left eigenvector of *JR*, and ξ_i is the i[th] column of the right eigenvector. The i[th] mode of the Q-V response is defined by the i[lh] eigen value d_i, and the corresponding right and left eigenvectors ξ and h_i, Equation (3.58) can be presented as;

$\eta \Delta V = \wedge^{-1} \eta \Delta Q$ (3.60)

By defining $v = \wedge^{-1}$ as the vector of modal voltage changes and as the vector of modal reactive power changes, the first-order equations can be broken down given as;

$v = \wedge^{-1} q$ (3.61)

Therefore, for the i[th] mode, to obtain

$v_i = \frac{1}{\delta_i} q_i$ (3.62)

At the instant where $d_i > 0$, the i[lh] modal voltage and the ith modal reactive power changes align in the same direction, indicating voltage stability of the system; whereas $d_i < 0$ denotes the instability of the system. The magnitude of d_i signifies an average level of instability of the i[th] modal voltage. The smaller the magnitude of a positive d_i, the nearer the i[lh] modal voltage to experience instability. The system voltage collapse when $d_i = 0$, and is as a result of changes in the modal reactive power that causes an infinite change in the modal voltage.

A system voltage is assumed to be stable if the eigenvalues of J_r are all positive. However, in the analysis of dynamic systems the eigenvalues with negative real pails are stable. The interaction between system voltage stability and eigenvalues of the J_R matrix is best understood by relating the eigenvalues with the V-Q sensitivities of each bus (which must be positive for stability). J_r can be taken as a. symmetric matrix and therefore the eigenvalues of J_r are close to being purely real. If all the eigenvalues are positive. J_r is positive definite and the V-Q sensitivities are also positive, indicating that the system is voltage stable. The system is considered voltage unstable if one or more of the eigenvalues is found to be negative. A zero eigenvalue of J_r means that the system is on the point of voltage instability, In essence, small eigenvalue of J_r determines the proximity of the system to being voltage unstable (Enemuoh *et al.,* 2016). There is no need to evaluate all the eigenvalues of Jr of a large power system because it is known that once the minimum, eigenvalues become zero the system Jacobian matrix becomes singular and voltage instability occurs. Therefore, the eigenvalues that are vital are the critical eigenvalues of the reduced Jacobian matrix J_r. This implies that the smallest eigenvalues of J_r are taken to be the least stable nodes of the system. The rest of the eigenvalues are not considered because these nodes are considered to be vital in the determination of stability of the system. After the minimum eigenvalues and the corresponding eigenvectors have been calculated the participation factor can be utilized to identify the weakest bus in the system, the relative contribution of the power at bus k in mode i is given by the bus participation factor (Enemuoh, 2010)

$P_{ki} = \xi_{k2} \eta_{ki}$ (3.63)

Participation factors show the most critical nodes which can lead the system to instability. Generally, the higher the magnitude of the participation factor of a bus in a specific mode, the easier the solution that can be applied on that bus in stabilizing the node.

The flowchart developed for outlining the steps followed in the modal/eigenvalue analysis of the power system network is shown in Figure 3.3 given next page.

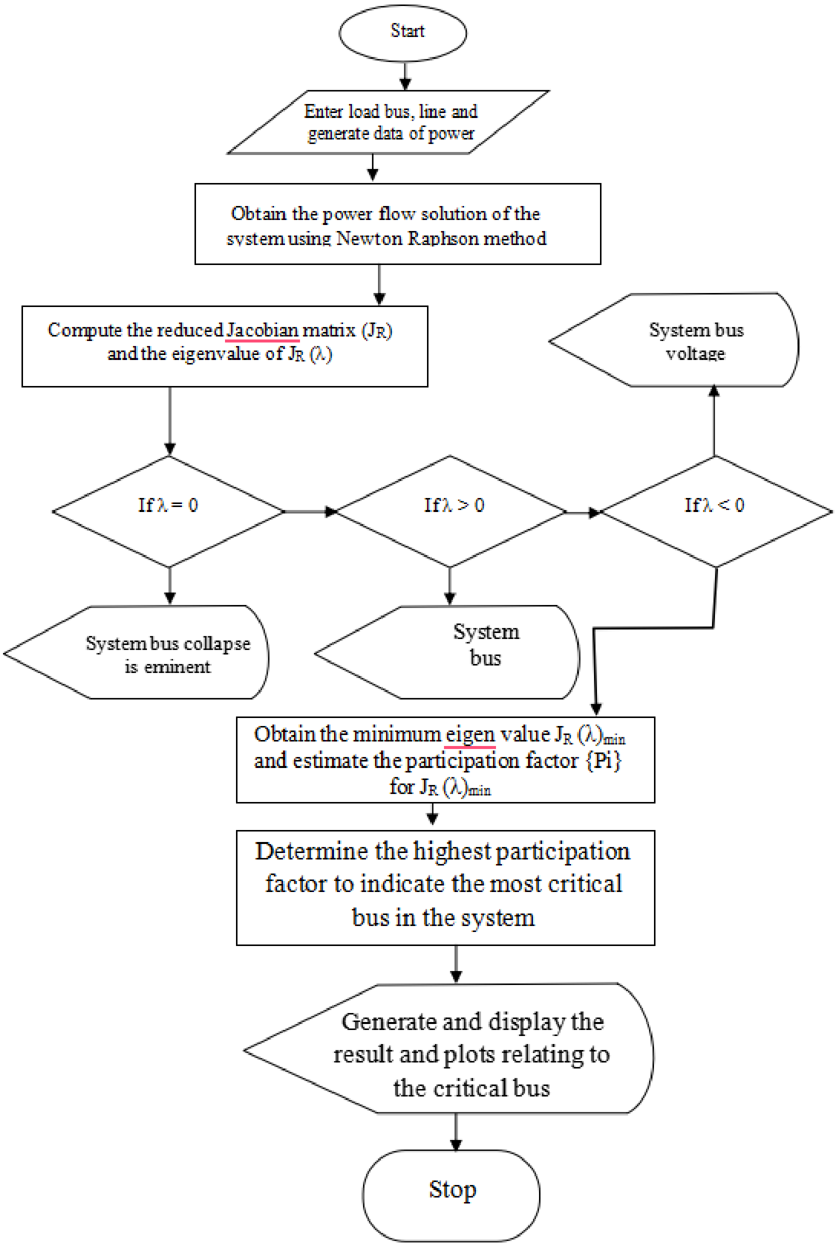

Figure 3.3: Algorithm for the modal analysis method of stability evaluation (Courtesy of Modern power system Analysis (Kothari &Nagrath)

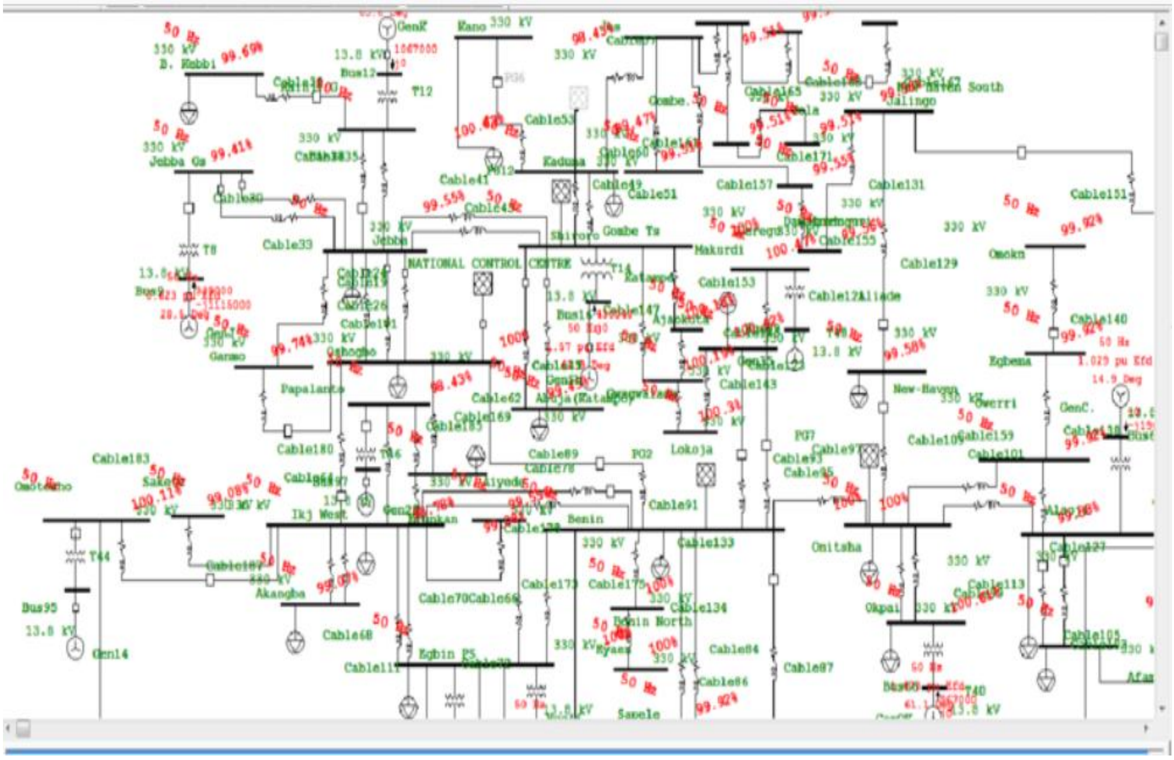

Figure 3.4: Shows the Single-Line Representation of the Existing Study Case (330KV Nigerian Network Simulated).

The single line diagram of 48-bus 330KV transmission network using Etap 19.0.1 are presented in Figure 3.4, for the analysis of voltage instability prediction.

3.18 Voltage Stability Indices

Application for Power Flow Solutions

This research considered the study of various line voltage stability indices (VSIs) for the assessment of voltage collapse. The indices are relied on the two bus – network, as represented as;

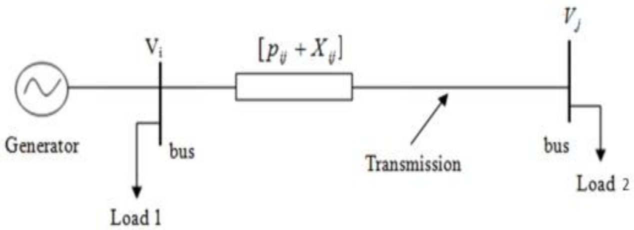

Figure 3.5: Single line representation of a two (2)-bus system

V_i and V_j : voltage at ith and jth bus.
δ_i and δ_j : power angle at ith and jth bus
θ_{ij}: Line impedance angle
P_i and P_j : Real power load at ith and jth bus
Q_i and Q_j : Reactive power load at ith and jth bus
R_{ij} and X_{ij} : Resistance and reactance of the line correcting ith and jth bus
I_{ij} : Brand –current of each line connecting ith and jth bus
$\delta = \delta_i - \delta_j$: Power angle difference between sending and receiving end buses
The five (5) governing equations in line with power flow equations are stated as;

Analysis 1: Fast voltage stability index (FVSI) given as;

$$FVSI_{ij} = \frac{4 \times Z_{ij}}{V_i^2 x_{ij}} \qquad (3.64)$$

This analysis tool is considered for stable operation of the system that is the value of FVSI should be maintained less than one (1) numerically. The values close to one indicates, that particular line is close to instability point; that may lead to voltage collapse in the system.
Where,
Z_{ij}: impedance between bus *i* and *j*
V_i : voltage at sending-end
X_{ij} : reactance at bus *i* and *j* respectively

Analysis 2: Line Stability Index (LMN)
According to Moghavemmi *et al.* (2019) proposes LMN based on power flow this is a single line, two-bus system, represented mathematically as;

$$lmn = \frac{4X_{ij}Q_j}{V_i sin(\theta_{ij}-\delta)} \quad (3.65)$$

That is the values of LMN close to one indicates that the system is losing its stability leading to voltage collapse. This means that for stable operation of a system, the value should remain less than one, to enhance reliable power supply.

Analysis 3: Line Stability Factor (LQP)
Essentially, according to Moghavverni *et al.* (2019) formulated LQP based on the same concept of power flow equations, given as;

$$LQP = 4\left(\frac{X_{ij}}{V_i^2}\right)\left(Q_j \frac{P_i^2 X_{ij}}{V_i^2}\right) \quad (3.66)$$

That is for stable operation,
LQP <1

Analysis 4: Voltage Stability Index (LD)
The index is also developed to determine voltage stability conditions; this is stated mathematically as;

$$Ld = \frac{\sqrt[4]{(P_i^2+Q_i^2)(R_{ij}^2+X_{ij}^2)}}{V_i^2} \quad (3.67)$$

This mean that the system condition to be in proximity to voltage collapse for any value of LD close to one.

Analysis 5: Novel Line Stability Index (NLSI)
The NLSI are developed to describe the behavior of system conditions, for purpose of avoiding voltage instability. This is expected mathematically as;

$$NLSI = \frac{P_j R_{ij}+Q_j X_{ij}}{0.25V_i^2} \quad (3.68)$$

Essentially, it is required that for purpose of stability, NLSI should be less than one.

IV. RESULTS AND DISCUSSION

Determining the voltage magnitudes and phase angle, active and reactive power losses. The assessment of various voltage stability indices (VSIs) is presented to predict proximity of the transmission line close to voltage collapse. The predictive optimizer model is based on load flow numerical solutions. These indices considered the fast-voltage stability index (FVSI), line stability index (LMN), line stability factor (LQP), voltage stability index (LD) and Novel line stability index (NLSI) respectively. The simulation of the existing transmission network (330kv) shows violations of the buses voltage and transmission line system deviations from standard statutory limits. The network was simulated using ETAP-application tool which is verified by the five (5) system voltage indices in their respective degree of violations for network collapse.

4.1 Result of PV Curve for Existing Network Condition

Figure 4.1 shows a comparison P-V curve plot used for analyzing steady state voltage stability. The blueline curve shows the operating point of Bus 12 (New Heaven) for base case network condition. The curve indicates how the bus voltage falls as real power increases to the point of voltage collapse which defines the maximum demand that can be served after which the system will not recover. A quick look at figure 4.1 shows that the operating voltage of Bus 12 (New Heaven) is 93.925% at 710.0 MW loading and can be increased by1597.5MW before a voltage collapse can be seen beyond which the system will not recover, the operating voltage at the point of collapse is 58.198%at 2307.5 MW loading.
The presentation of voltage stability predictive indices, for the determination of system operating condition: table, unstable, critical as shown in table 3.5 etc.

On the other hand, Figure 4.2 shows a P-V curve plot used for analyzing steady state voltage stability. The blueline curve shows the operating point of Bus 18 (Ugwaji) for base case network condition. The curve indicates how the bus voltage falls as real power increases to the point of voltage collapse which defines the maximum demand that can be served after which the system will

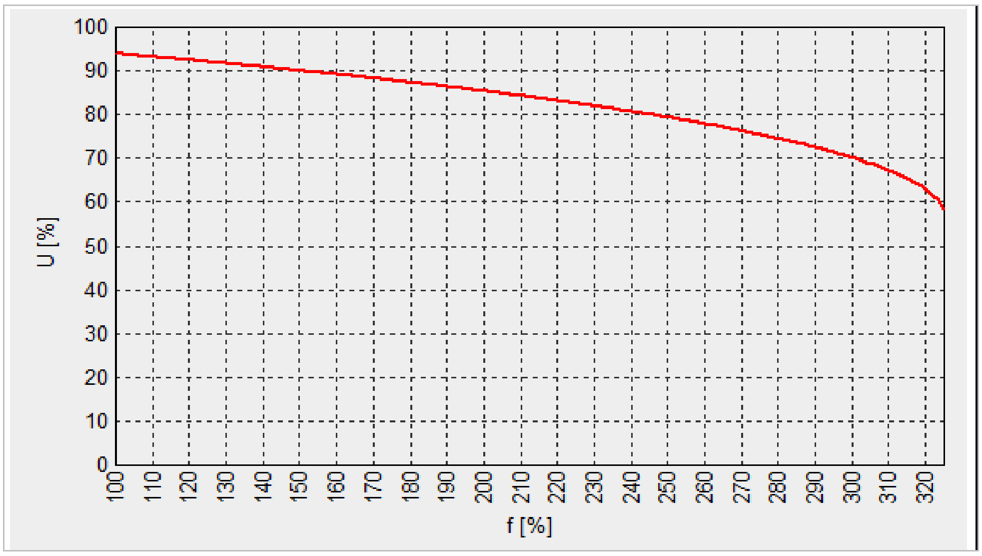

Figure 4.1: Base Case P-V Curve for Bus 12 (New Heaven)

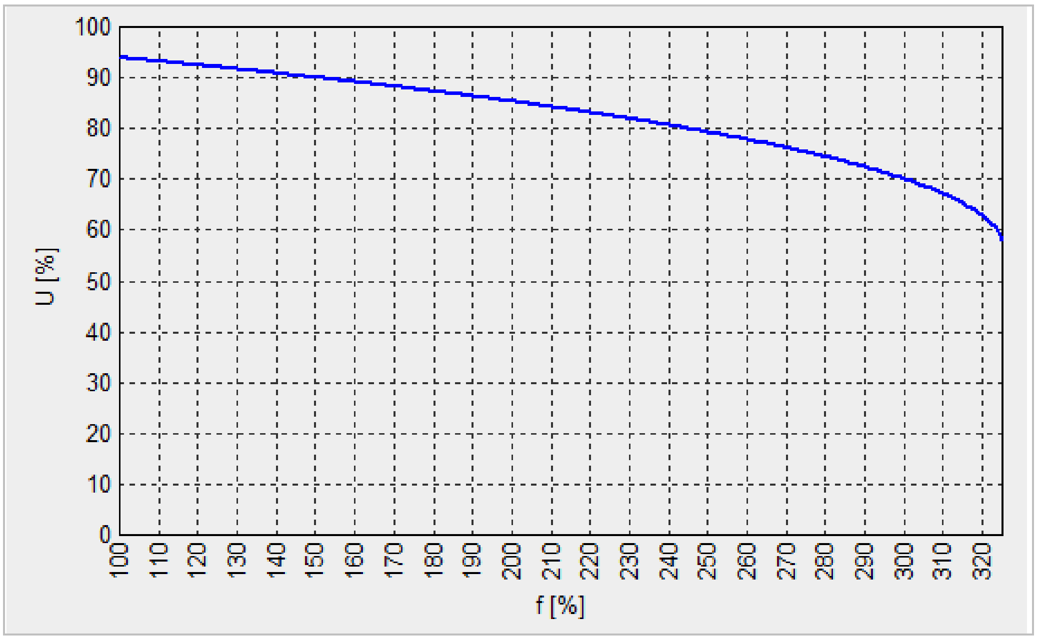

Figure 4.2: Base Case P-V Curve for Bus 18 (Ugwaji)

not recover. A quick look at figure 4.2 shows that the operating voltage of Bus 18 (Ugwaji) is 93.956% at 710.0 MW loading and can be increased by1597.5MW before a voltage collapse can be seen beyond which the system will not recover, the operating voltage at the point of collapse is 58.069%at 2307.5 MW loading.

4.5 Determination of Steady State
Operating Condition for Fortified Network

Table 4.1 shows the operating voltage of the fortified network when compensated with an SVC of 75Mvar capacity at bus 12 and 18 respectively (See Appendix D for base load flow simulation of fortified network). It can be seen from Table 4.1 that all buses are within the acceptable statutory limit of 0. 95p.u - 1.05 with no bus voltage violation. A quick look at the Table 4.1 shows that Bus12: 0.984p.u and Bus18:0.985 are within the acceptable statutory limit of 0.95p.u-1.05 with no bus voltage violation.

Table 4.1: Bus Operating Voltage for Base Case Network Condition

Bus No	Bus Name	Bus Type	Nominal kV	Operating kV	p.u
1	Adiabor TS	PQ	330	326.387	0.989
2	Afam GS	Slack	330	330.000	1.000
3	Aladja TS	PQ	330	329.145	0.997
4	Alaoji GS	PV	330	330.000	1.000
5	Alaoji TS	PQ	330	329.455	0.998
6	Asaba TS	PQ	330	322.077	0.976
7	Azura GS	PV	330	330.000	1.000
8	Benin TS	PQ	330	329.494	0.999
9	Delta GS	PV	330	330.000	1.000
10	Ikot-Abasi TS	PQ	330	327.570	0.993
11	Ikot-Ekpene TS	PQ	330	329.420	0.998
12	New Heaven TS	PQ	330	324.842	0.984
13	Odukpani GS	PV	330	330.000	1.000
14	Okpai GS	PV	330	330.000	1.000
15	Onitsha TS	PQ	330	324.922	0.985
16	Onne TS	PQ	330	328.227	0.995
17	Sapele GS	PV	330	330.000	1.000
18	Ugwaji TS	PQ	330	325.076	0.985

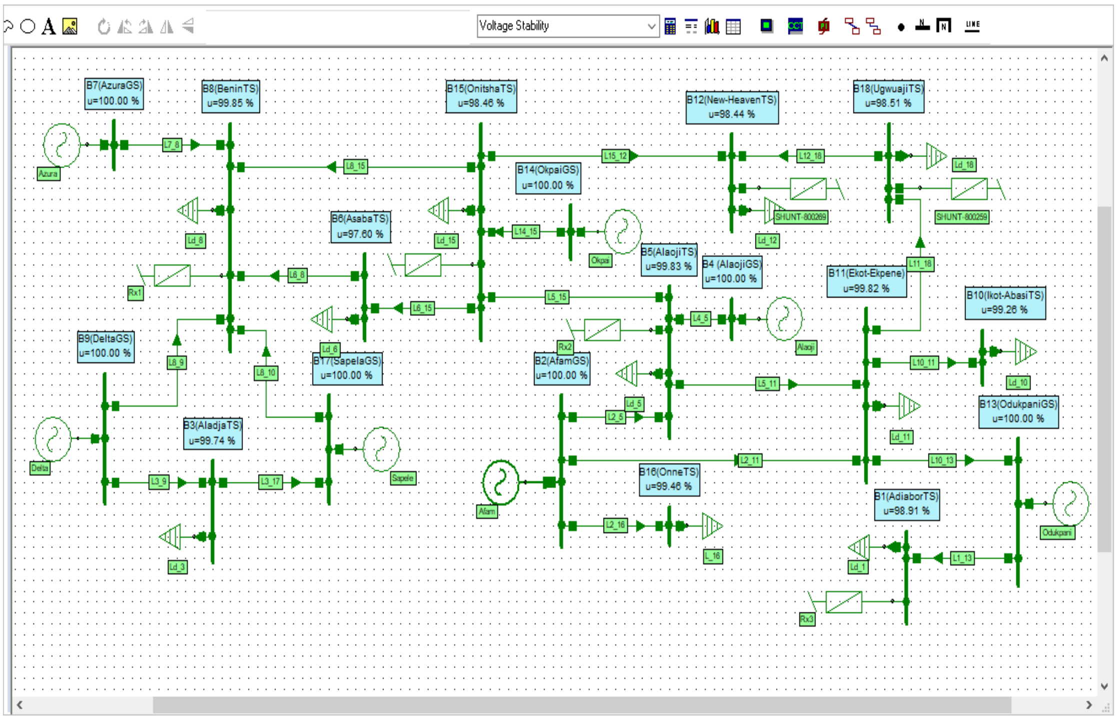

Figure 4.3 Single Line Diagram of Improved Network

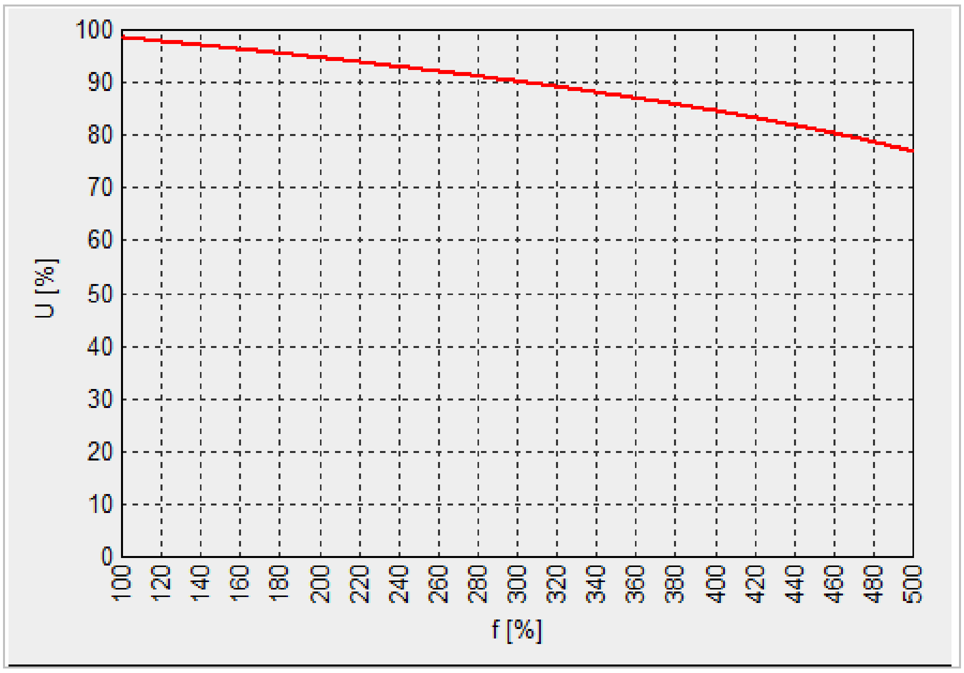

Figure 4.4: Improved P-V Curve for Bus 12 (New-Heaven)

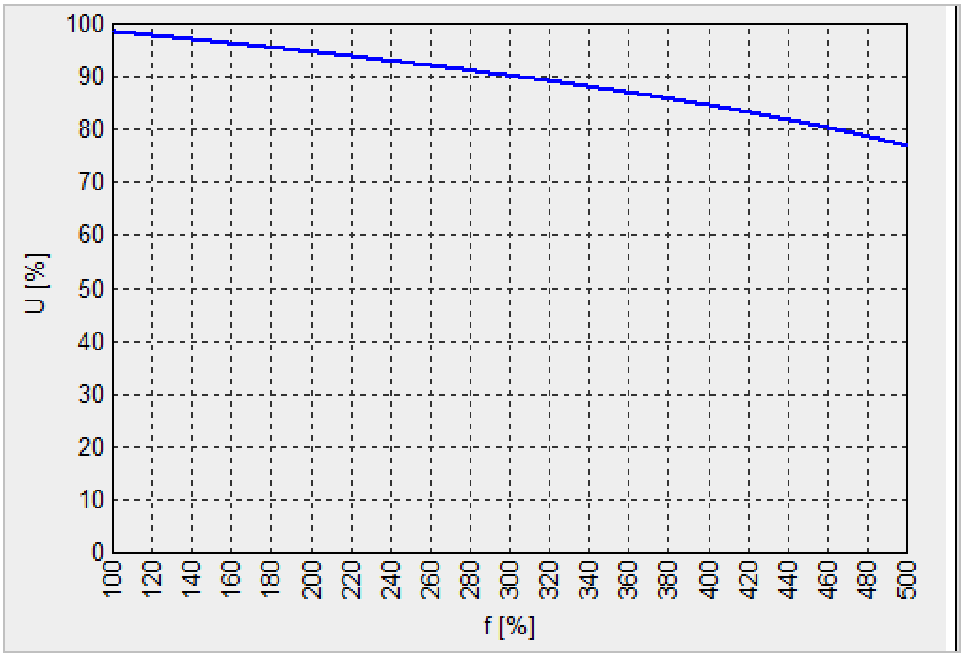

Figure 4.5: Improved P-V Curve for Bus 18 (Ugwaji)

4.6 Result of Improved PV Curve in the improved Network Condition

Figure 4.3 shows the improved P-V curve plot used for Bus 12 (New Heaven) when a controlled SVC are installed. It is seen from Figure 4.3, that the operating voltage is increased to 98.437% at 710.0 MW loading and can be increased by 2840 MW before a voltage collapse can be seen beyond which the system will not recover, the operating voltage at the point of voltage collapse is 76.821%at 3550 MW loading. Therefore, it is seen that with SVC installed at Bus 12 the load ability of bus 12 (New Heaven) can be increased by 1242.5MW5

Figure 4.4 shows the improved P-V curve plot used for Bus 18 (Ugwaji) when an SVC are installed. It is seen from Figure 4.4, that the operating voltage was increased to 98.508% at 710.0 MW loading and can be increased by 2840 MW before a voltage collapse can be seen beyond which the system will not recover, the operating voltage at the point of voltage collapse is 76.801% at 3550 MW loading. Therefore, it is seen that with SVC installed at Bus 18 the load ability can be increased by 1242.5MW.

Remarkably, five (5) voltage stability indices (NLSI, FVSI, LMN, LQP, LD) has been strategically employed to assess and predict maximum capacity limit in each scenario of voltage collapse within the 330kV long transmission network. These indices, NLSI, FVSI, and LMN exhibit predictive behaviors regarding system voltage collapse. In the context of the study, the Novel Line Stability Index (NLSI) stands out as gives superior and rapid predictive capability in identifying voltage instability. Notably, critical nodes such as Shiroro, Okpai, Kumbotoso, Jos, Makundi, Damaturu, Ikeja-west, Ikot-Ekpene, Ayede, Aja, and Egbin—classified as critically overloaded buses surpassing its maximum loadability limits which are effectively identified by NLSI. Essentially, LMN and FVSI tends to show better prediction as compared to other predictive indices.

The developed 2nd order quadratic equation $\left|V_y\right|^2 - \left|V_x V_y\right| - \frac{Q_y}{B_{xy}} = 0$ and its solution $V_{y1,2} = \frac{-V_x}{2} \pm \sqrt{\frac{\left|Vx\right|^2}{2} + 4.\frac{Q_y}{B_{xy}}}$ encapsulates the intricate interplay between Vy1 and Vy^2 (representing receiving end voltage) concerning Vx (the sending end voltage), presenting a mathematical model essential in various engineering disciplines. Primarily, this model will find significant application in power systems analysis, while maintaining voltage stability. Within the complex network of power transmission and distribution, voltage stability ensures the reliable operation of electrical grids, safeguarding against potentially catastrophic disruptions. By providing a framework to assess the behaviour of Vy^1 and Vy^2 in response to changes in Vx, the equation offers invaluable insights into the dynamics of voltage stability. This will play a pivotal role in the design, optimization, and management of power systems, enabling system engineers to address challenges and enhance resilience of electrical grids. Thus, the equation serves as a cornerstone in the quest for a robust, efficient and sustainable energy infrastructure capable of meeting the ever-growing demands of modern society.

V. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study x-rayed the activities of voltage control and stability problems are not new to the electric utility industry and consumer at the receiving ends. Nigeria power network consists of limited numbers of generating transmission stations situated at remote areas. This study has considered and determined the collation of numerical data from existing 330Kv and 132Kv grid network for analysis and evaluation.

The research study has also formulated governing equations (model analysis, Newton-Raphson load flow solution, five predictive optimizers: (FVSI, LQP, LMN, LD AND NLSI) for the prediction of system condition. Essentially, the application of the modal analysis with participation factor tool was used as criteria for determining weak and stronger bus under investigation. That is the critical buses exhibits higher participation factor close or greater than 1, particularly the highest participation is bus 1-2: New heaven followed by Bus 18: Ugwaji, these buses are selected as candidate buses targeted intervention such as reactive power support or load shedding to enhance system stability and prevent voltage collapse.

The results obtained from five (5) predictive indices shows predictive capacity of line voltage instability of the 330Kv and 132Kv network with FVSI, LMN, and NLSI as stronger predictive tool over LD and LQP. Consequently, the existing network was modeled in a single line diagram using Neplan software (20buses) and Etap – software application tool for 48-buses which are used as study case under investigation. The network was modeled and simulated while violated buses are been compensated using static var.

The 330Kv network was modeled using Neplan -555 using embedded model analysis tool to determine the participation factor for voltage stability in line with eigen-vector and eigen-values. Similarly, 330Kv network 48-buses was modeled using electrical transient analyzer (Etap 19.0.1) to evaluate voltage stability limit for instability condition using predictive optimizer (FVSI, LMN, LQP, LD, NLSI)

5.3 Recommendations

Considering the results above and conclusion reached, the research recommends for solutions to challenges in generation and in transmission, which include:

(i) All generation stations should be on free governor mode of operation.
(ii) GENCO's should harmonize gas pipeline outages with gas turbine maintenance.
(iii) GENCO's should adhere to its declaration in accordance with NERC Order.
(iv) Acquisition of sufficient gas for generation to match demand.
(v) Gen stations should abide by NCC instructions on dispatch of both Active (MW) and Reactive power (MVAr)
(vi) The Annual Maintenance Plan should be maintained
(vii) Provision of SCADA/EMS facilities. (20.2.3. The System Operator shall have information available for System incident analyses by means of: (a) The System Operator's SCADA system(s) and other data collection systems). The new SCADA system will ensure visibility of all the existing 330kV, 132kV and Power Generation

(viii) Stations with allowances for future stations.
(ix) Upgrade of aged transformers and re-conducting of transmission lines
(x) Provision of Hotlines communication to NCC.
(xi) Provision of spare part for adequate maintenance.
(xii) Provision of spinning reserve.
(xiii) Provision of adequate Voltage compensating devices.
(xiv) Proper relay coordination across the entire power supply chain to avert uncoordinated and spurious tripping

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