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Analysis of Maximium Loadability of Weak Buses in the Nigeria 330kV Integrated Power System using PV and QV Curves

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ABSTRACT: Due to the frequent system collapse and blackouts in power system network nowadays, identification of weak buses and determination of maximium loadability points of buses have become necessary. This paper presents the determination of the maximium loadability points of weak buses in the Nigeria 330kV transmission network. First, load flow simulation was conducted in the developed model of the 56-bus power system network using Newton Raphson method in Electrical Transient and Analyzer Program (ETAP), weak buses were identified. The real and reactive power of the weak buses were varied in increasing steps and the voltage at each step were recorded. The PV and QV curves of the weak buses were plotted and the maximium real and reactive power at each bus were determined. This will serve as a guide to the power system operator on the limit of real and reactive power of load that can be connected to buses.

KEYWORDS: Maximium loadability, weak buses, the Nigeria 330kV network, PV curve, QV curve, Bifurcation

I. INTRODUCTION

Nowadays, many power systems around the world especially in developing countries are overstressed due to increasing electrical power demand, inadequate power generation to meet the demand, long, aged, fragile and limited transmission capacity, lack of or slow pace of network expansion and lack of political interest to invest on power system infrastructures. The aftermath of which is the regular violation of voltage stability limits, voltage collapse and blackouts experienced in many parts the world and Nigeria [1]. The increasing power demand have been a source of power system stability problem especially voltage stability problem. When the load power demand is higher than the power generation especially when reactive power demand of the load is greater than the reactive power generation or support, voltage reduces. Voltage also reduces when there is high voltage drop in transmitting real and reactive power over a long transmission lines. Also, transmission network itself consumes reactive power at heavy loading due to the inductive reactance of the transmission line. The reduction in voltage continues as additional load is added until a point where the voltage falls outside the acceptable limit of ±5% of the nominal value of the voltage and results to voltage instability leading to voltage collapse and total blackout. The point before voltage collapse is called maximum loading point.

Maximium loading point defines the point of maximum real and reactive power of the load that can be connected to a bus or area beyond which there will occur voltage collapse. It is important to know maximium loadability point in order to determine the stability margin in power system, size and optimal placement of reactive power compensators. Different types of methods are used to assess the maximium loadability of buses in a power system. Some of the methods are line and voltage stability indices, singular value decomposition, continuation power flow method, sensitivity analysis, and modal analysis. The Line Stability Indices (L_{mn}) and Fast Voltage Stability Index (FVSI) have been widely used to estimate maximium loadability of buses in power system [2-4]. The line stability indices is developed based on power transfer through a single line while Fast Voltage stability Index (FVSI) is obtained from the voltage quadratic equation at the receiving bus on a two-bus system. In each index, the value must be lower than 1.0 for the system to be stable that is the value 1.0 signifies the point of maximoium loadability point. In [5], the line stability indices has been proposed to estimate maximum loadability for weak bus identification. The study was achieved by modelling and simulation using MATLAB 2015 environment. The IEEE 14 bus test system, IEEE 30 bus test system and a typical IEEE 118 bus test system were used to demonstrate the effectiveness of the proposed technique. Two indices; the fast voltage stability indices (FSVI) and Line stability index were used to identify the weak buses and maximum loadability. Buses were ranked in ascending order to sort out weak buses and maximium loadability of the buses. The bus with the smallest loadability is ranked the highest which is identified as a weak bus. The point at which FVSI is close to unity indicates the maximium loadability point. The shortcomings of the line stability index and fast voltage stability index is the neglect of real power it their formulation and as such may not give accurate estimation of

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maximium loadability. Another stability index called Line Stabilty Factor (LQP) considers the real power in its formulation. In a similar way to L_{mn} and FVSI the value must be below 1.0 for the system to be stable [6]. In [7], four line stability indices, Lmm, LVSI, LQP and NVSI were comprehensively analysed. Their drawbacks and advantages were presented. It was concluded that the performance of these indices is not always good and highly depended on the power system structure and operating point.

The singular value decomposition is based on linearised power flow equations. This involves determination of the closeness of the jacobisn matrix of the power flow equation to becoming singular. In the analysis, the load is increased and the power flow jacobian matrix is computed. The loadability is reached when the smallest singular value of determinant of the jacobian matrix becomes zero (0)[8, 9]. From the operating point to the bifurcation or nose point, the jacobian matrix of the power flow equation tends to be nonlinear making it difficult to determine the maximium loadability point and degree of voltage stability. The modal analysis is another method that can be used for assessment of voltage stability and maximium loadability, it is based on linear approximation of the steady state system model. It involves computing the smallest eigenvalues and associated eigenvectors of the reduced jacobian matrix obtained from the load flow solution that relates reactive power sensitivity to voltage magnitude. The eigenvalues and eigenvectors are used to calculate bus, branch and generator participating factors. The smallest value of eigenvalues identifies the critical mode of the system [10, 11]. The critical state of the power system and maximum loading can be evaluated using sensitivity analysis method [12]. It is formulated from the sensitivity matrix from power flow equations. It involves state variables and control variables. The proximity of power system to instability is determined by the increase in the sensitivity coefficient. It is simple and straight forward method but its drawback is the inability to compute accurate state of stability in a complex networks.

Due to the drawbacks of some of these methods, researchers are now employing advance methods to determine voltage stability margin and maximium loadabiity points of buses in power system. Novel approaches to assess voltage stability and maximium loadability such as the voltage instability predictor (VIP)[13] , Artificial intelligent Algorithm [14] as well as line voltage stability index (LVSI) based on ABCD parameters of transmission line to include line charging capacitance and resistance of line that have been neglected by the existing voltage stability indices [15] and measurement [16] have been proposed. In the VIP, the impedance of the load is compared with the Thevenin equivalent impedance of the rest of the system and the point where the two impedances are equal determine the maximium power transfer. In [17], a Chaotic Mutation Immune Evolutionary Programming has been proposed to identify maximium loadability in power system under N-1 contingency in a transmission line. It was formulated the chaotic based mutation optimisation technique with several constraints and used to determine the optimal maximium loadability of an optimal bus under scheduled line outage contingency. The fast voltage stability index was used to identify the most critical line outage. They tested their proposed technique using the IEEE 30-bus reliability test system. The results of their tests showed the effectiveness of the proposed technique to determine the maximium loadability of the optimal bus during N-1 contingency. Line stability indices are easily computed and can be used to identify weak areas of the power system but they cannot accurately predict the collapse point and maximium loadability point. Yang Weng etal in [18] developed a linear programming framework using rectangular coordinates for complex voltages and provided an integrated geometric view of active and reactive power flow equations on loadability boundaries. The standard IEEE 14-bus test system was used to verify the proposed method. Numerical results demonstrate the capability of the method in computing the loadbility point and margin. It was concluded that this proposed method is computationally more efficient than the existing methods since it does not require solving nonlinear power flow equations or eigenvalues.

In [19], it was patented a method of computing steady-state voltage stability margins of power system based on introducing AQ bus with specified bus angle and reactive power consumption of a load bus. The angle of separation between the swing bus and the AQ bus is varied to control the power transfer to the load. This method eliminates the singularity of Jacobian maxtrix in Newton Raphson load flow as it approach maximium loading point. The formulation of this method eliminate the real power and considered a constant power factor load. This method was applied to a 48 machine system and the results shows that it can be used to calculate the stability margins of a power system faster compared to other methods. Since it does not consider real power flow in the determinations of the stability margins, it may not give accurate results in all operating conditions.

Several researchers have used the continuation power flow to analyse voltage stability and estimate maximium loadability of power system [20-23]. In continuation power flow, the predictor-corrector process is used to find the next stable operating point for a given load. The limitation of the continuation power flow method is the computational effort and time required to get a solution and in most cases the solution diverges. E. N Ezeruigbo [24] carried out voltage stability analysis of Nigeria 330kV Power grid using static P-V plots. Their study emphasized on the performance of static PV plots in which they selected source and sink bus based on the interest to the location around the south east geopolitical zone of Nigeria. However, their results shows maximium loading of the selected buses,

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emphasis was not given to the weak buses. The advantage of PV and QV curves is that, they are easy to calculate, constructed and the maximium loadability point can easily be identified, and in this study, the PV and QV curves are used to estimate the maximium loadability point of the power system. Knowing the maximium loadability point will help in operating the power system within the stability region and avoid or reduces system collapse. Once the power system operator (PSO) know the maximium loadability of buses, it becomes a guide to the maximium allowable load that can be accommodated in the buses to maintain voltage stability in the system.

II. REAL AND REACTIVE POWER INJECTION INTO A BUS

The real and reactive power injection into a bus can be obtained starting with the relationship between the bus voltage, current and impedance as given in(1).

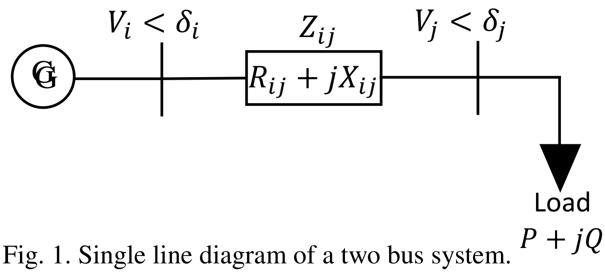

Fig. 1. Single line diagram of a two bus system.

Considering an i_{th} bus as shown in a single line diagram in Fig. 1, the current injection into the i_{th} bus I_i is a function of the voltage at i_{th} bus, V_i and the impedance of the line, Z_{ij} between the i_{th} bus and another bus say j_{th} bus given as;

$$I_i \frac{V_i}{Z_{ij}} \tag{1}$$

In order to eliminate the burden of calculation in(1), the relationship between impedance and admittance can be used and (1)becomes;

$$I_i = V_i y_{ij} \tag{2}$$

Where, y_{ij} is the admittance of the line between bus i and j.

In an n-bus power system, the current injection into i_{th} bus is calculated based on Kirchhoff Current Law (KCL) given as;

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} V_j y_{ij} \quad j \neq i \tag{3}$$

Equation (3) can be written in terms of the bus admittance matrix Y_{ij} as,

$$I_i = \sum_{j=1}^{n} Y_{ij} Y_j \text{, for } i = 1, 2, 3, \ldots\ldots n \tag{4}$$

Where, V_i and V_j are phasors having magnitude and angle given as,

$$V_i = |V_i| \angle \delta_i = |V_i| \left(\cos \delta_i + j \sin \delta_i \right) \tag{5}$$

$$V_j = |V_j| \angle \delta_j = |V_j| \left(\cos \delta_j + j \sin \delta_j \right) \tag{6}$$

And

$$Y_{ij} = |Y_{ij}| \angle \theta_{ij} = |Y_{ij}| \left(\cos \theta_{ij} + j \sin \theta_{ij} \right) \tag{7}$$

Equation (4) can be expressed in polar form as

$$I_i = \sum_{j=1}^{n} |Y_{ij}| \angle \theta_{ij} \times |V_j| \angle \delta_j = \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \tag{8}$$

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Therefore, the complex power at the i_{th} bus is given by

$$P_i - jQ_i = V_i^* I_i = V_i^* \sum_{j=1}^{n} Y_{ij} V_j \tag{9}$$

$$P_i - jQ_i = V_i^* I_i = |V_i| \angle -\delta_i \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j \tag{10}$$

Where, P_i is the real power in bus-*i* and Q_i is the reactive power in bus-*i* and V_i^* is the conjugate of the voltage at bus-*i*. Substituting equations(5), (6), and (7) into (10) and simplify by separating, the real and reactive power at i_{th} bus are given by;

$$P_i = \sum_{j=1}^{n} |Y_{ij}||V_j||V_i| \cos(\theta_{ij} + \delta_j - \delta_i) \tag{11}$$

$$Q_i = -\sum_{j=1}^{n} |Y_{ij}||V_j||V_i| \sin(\theta_{ij} + \delta_j - \delta_i) \tag{12}$$

Equations (11) and (12) are simultaneous nonlinear equations in terms of $|V|$ and δ. These equations can be solve iteratively using Gauss Seidel, Newton Raphson, and Fast Decoupled. In this study, the Newton-Raphson method is used to perform the load flow [25, 26].

III. REAL POWER-VOLTAGE (PV) AND REACTIVE POWER-VOLTAGE (QV)CURVES

The Real Power-Voltage (PV) and Reactive Power-Voltage (QV) curve shows a nonlinear relationship between the bus voltage and the variation of real and reactive power of a bus or an area of a power system. PV curve is a graph of load bus voltage magnitude on the vertical axis against the real power on the horizontal axis for a given power factor. The same applies to the QV curve. In plotting a PV or QV curve, the power factor is kept at a fixed value while the real power, P or the reactive power, Q is varied in increasing steps while the voltage magnitude is recorded. The real power has an inverse relationship with the voltage magnitude, as the real power is varied in an increasing order, the bus voltage magnitude reduces until a point called a nose point at bifurcation is reached. At this point, additional real and reactive power cannot be accepted by the power system. PV curve gives the highest real power of a load that can be connected to a particular area or bus in a power system. Different buses have different PV and QV curves. Therefore different buses have different maximium real and reactive power.

IV. FORMLATION OF POWER VOLTAGE (PV) CURVE MAXIMIUM LOADABILITY EQUATION

Fig. 2 shows a single line diagram of a single machine 2-bus network consisting of a generator as a source of voltage connected to bus 1 with a voltage, $E\angle\delta$ and a load $P + jQ$ connected to bus 2 with a voltage $V\angle 0$ fed by an infinite bus transmission system.

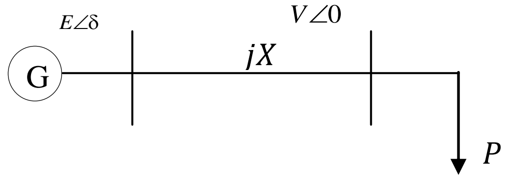

Fig. 2 A single line diagram of a single machine network

Considering the transmission line resistance to be negligible, the voltage stability of a simple machine power system is given as

$$V = E - jXI \tag{13}$$

Where, V is the phasor voltage $V\angle 0$ at bus 2, E is the phasor voltage $E\angle\delta$ at bus 1, X is the impedance of the line neglecting the resistance, I is the current flowing from bus 1 to bus 2, δ is the power angle.
The complex power of the load is given by

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$$S = P + jQ = VI^* \tag{14}$$

Making I the subject from (13) and substitute into (14), the complex power becomes,

$$S = V\left(\frac{E^* - V^*}{-jX}\right) \tag{15}$$

Equation (15) can be expressed in a rectangular form as,

$$S = \frac{j}{X}(EV\cos\delta + jEV\sin\delta - V^2) \tag{16}$$

$$S = \frac{jEV\cos\delta - EV\sin\delta - jV^2}{X} \tag{17}$$

Assuming a constant power load, the real power, P and reactive power, Q transferred from bus 1 to bus 2 can be obtained by separating the real and imaginary parts of (17) expressed as,

$$P = -\frac{EV\sin\delta}{X} \tag{18}$$

$$Q = \frac{EV\cos\delta}{X} - \frac{V^2}{X} \tag{19}$$

Making $\sin\delta$ and $\cos\delta$ the subject, (18) and (19) becomes,

$$\sin\delta = \frac{-PX}{EV} \tag{20}$$

$$\cos\delta = \frac{QX + V^2}{EV} \tag{21}$$

Squaring both sides of (20) and (21) the expression in

$$\sin^2\delta + \cos^2\delta = \left(\frac{-PX}{EV}\right)^2 + \left(\frac{QX + V^2}{EV}\right)^2 \tag{22}$$

Since

$$\sin^2\delta + \cos^2\delta = 1 \tag{23}$$

$$1 = \left(\frac{-PX}{EV}\right)^2 + \left(\frac{QX + V^2}{EV}\right)^2 \tag{24}$$

Multiplying both sides of (24) by $(EV)^2$, the voltage equation can be written as

$$V^4 + (2XQ - E^2)V^2 + X^2(P^2 + Q^2) = 0 \tag{25}$$

Equation (25) is then used to plot the PV curve and QV curve.

V. MATERIALS AND METHOD

This study involves modelling and simulation in a computer based software. To estimate the maximium loadability point using PV curve and QV curve, the existing 56 bus Nigeria 330kV transmission system network is used. The single line diagram of the power system is shown in Fig. 3. It consists of 56 buses, 22 generators, and 9,454km of transmission lines. First a model of the power system was developed and load flow simulation tests was carried out with the developed model of the power system in Electrical Transient and Analyzer Program(ETAP) software based on Newton Raphson method to determine the weak buses. The input data such generator bus data, transmission line data and load bus data for the simulation model were obtained from Transmission Company of Nigeria. The real and reactive power at the weak buses are then increased in steps at a fixed power factor of 0.85**.**

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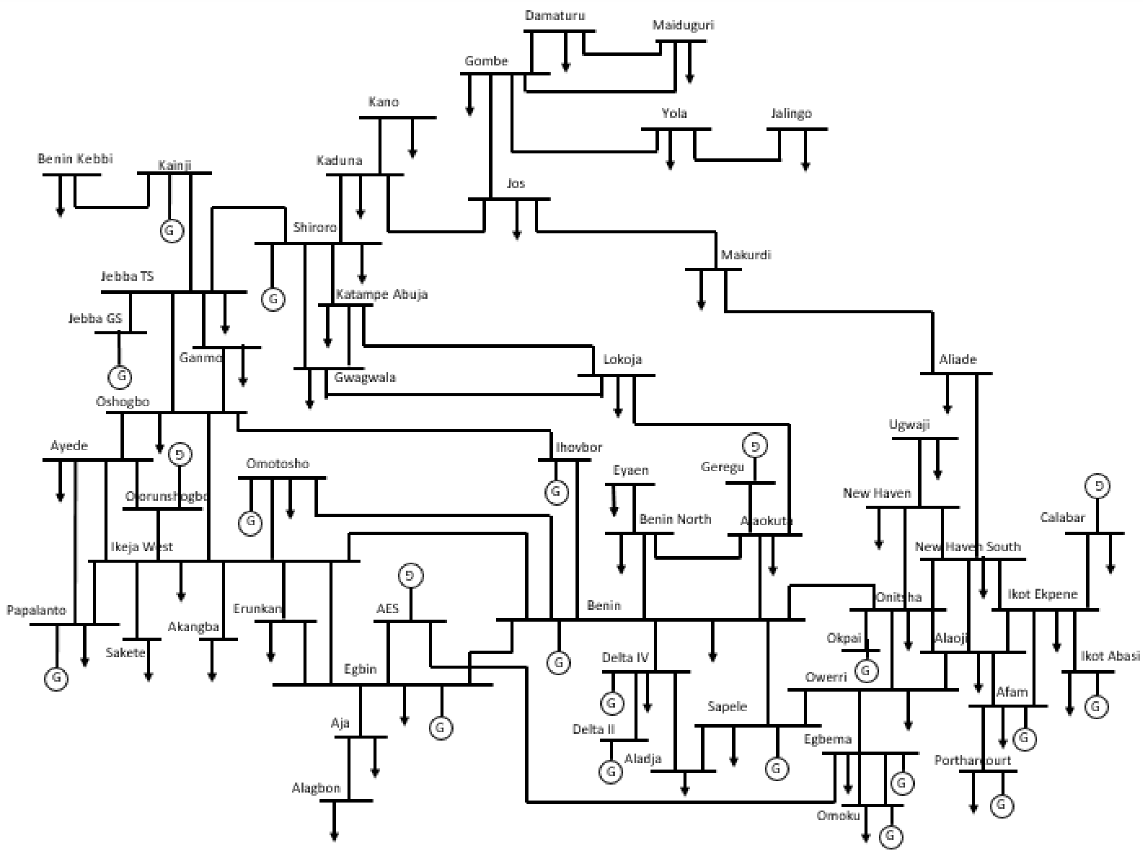

Fig. 3. Single line diagram of the 56-bus Nigerian 330kV Transmission Network

VI. RESULTS AND DISCUSSION

The ETAP simulation results of load flow analysis identified buses which voltage magnitude fall outside the statutory limit of 330kV±5% considered as the weak buses in the existing 56-bus Nigeria 330kV transmission network as shown in Table 1. Ten buses were discovered to be the weak buses in the power system with Kano bus being the weakest followed by Jalingo, Kaduna buses while Markurdi with 0.9432pu and Aliade with 0.9469pu are close to the lower voltage stability limit of 313.5%.

Table 1.0: Identified weak buses from simulation

S/N	Bus Name	Bus Nominal Voltage (kV)	Operational Voltage (kV)	V (pu)	Angle (^{0})
1	Kano	330	257.565	0.7805	-44.59
2	Jalingo	330	287.793	0.8721	25.51
3	Kaduna	330	291.489	0.8833	-34.56
4	Yola	330	294.36	0.892	-23.39
5	Damaturu	330	295.713	0.8961	-39.39
6	Maiduguri	330	295.713	0.8961	-39.98
7	Gombe	330	297.00	0.9000	-37.04
8	Jos	330	300.696	0.9112	-32.95
9	Makurdi	330	311.256	0.9432	-27.66
10	Aliade	330	312.477	0.9469	-26.18

Fig. 4 to Fig. 13 shows the bus voltage against the variation of the real and reactive power for the weak buses in the Nigeria 330kV transmission network. Fig. 4 shows the PV and QV curves for Kano bus, with the maximium real power, Pmax and reactive power, Qmax to be 171.7MW and 106.41MVAr respectively while Fig. 5 shows that of

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Jaligo bus which has a maximium real power of 76.5MW and reactive power of 47.41MVAr. The summary of the maximium loadability of each buses is shown in Table 2.

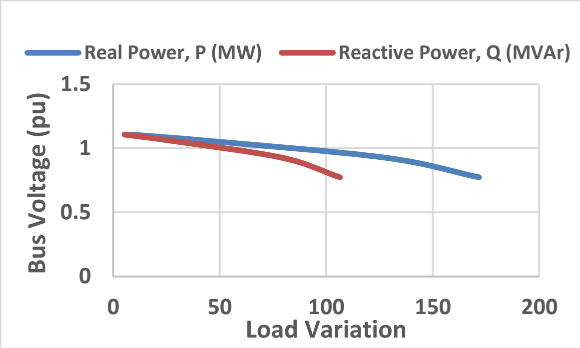

Fig. 4 PV curve and QV curve at Kano Bus

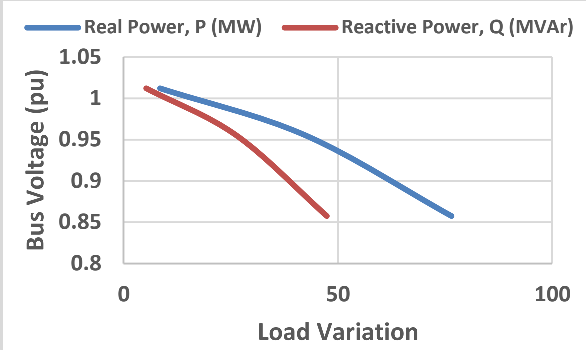

Fig. 5 PV curve and QV curve at Jalingo Bus

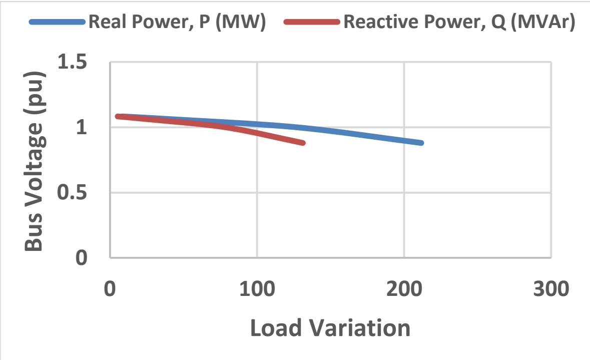

Fig. 6 PV curve and QV curve at Kaduna Bus

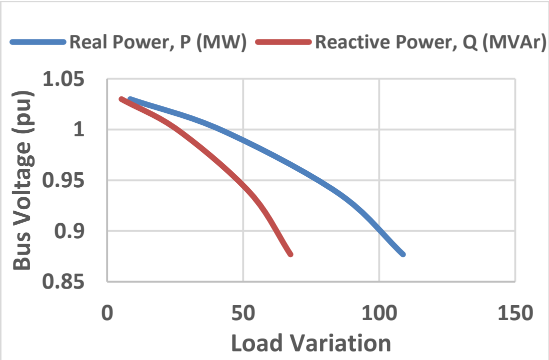

Fig. 7 PV curve and QV curve at Yola Bus

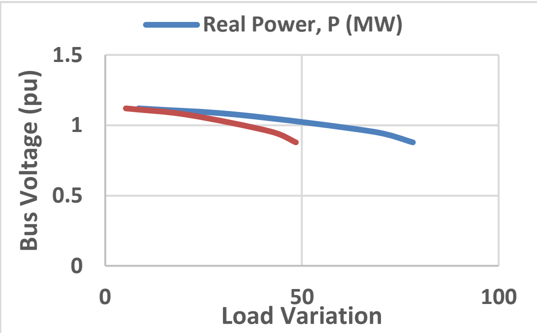

Fig. 8 PV curve and QV curve at Damaturu Bus

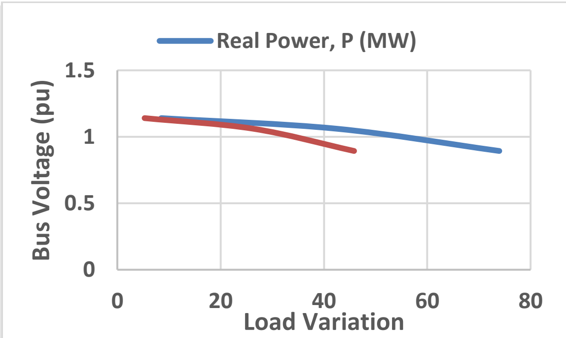

Fig. 9 PV curve and QV curve at Maiduguri Bus

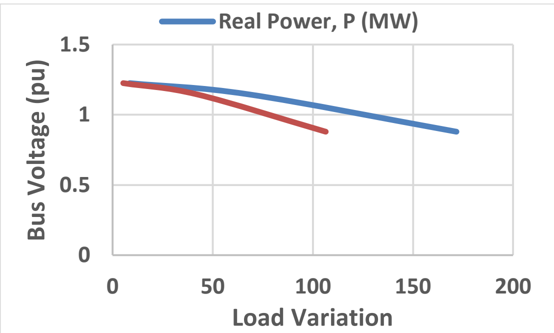

Fig. 10 PV curve and QV curve at Gombe Bus

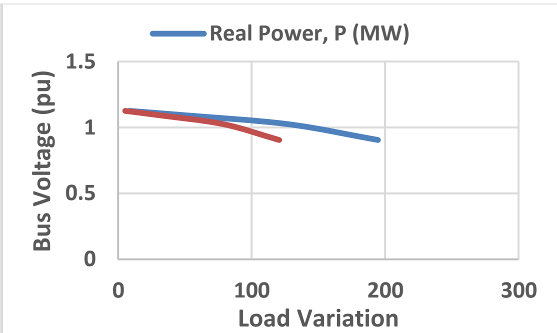

Fig. 11 PV curve and QV curve at Jos Bus

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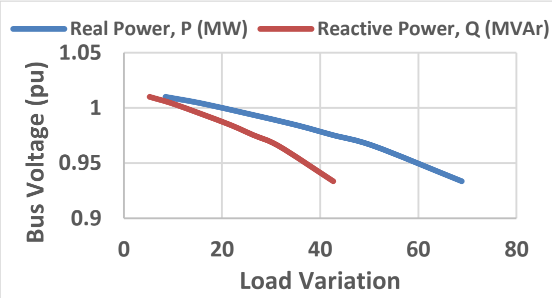

Fig. 12 PV curve and QV curve at Makurdi Bus

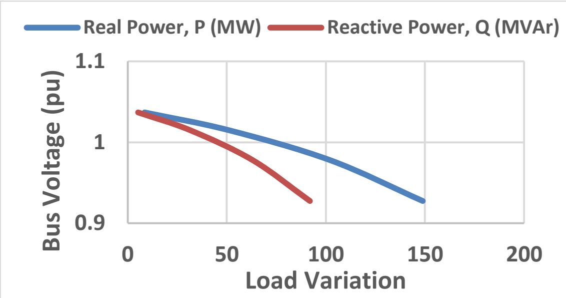

Fig. 13 PV curve and QV curve at Alaide Bus

Table 2: Maximium loadability points of the weak buses obtained from the PV and QV curves

S/N	Bus Name	Pmax (MW)	Qmax (MVAr)	V (pu)	Angle (^{0})
1	Kano	171.7	106.41	0.7805	-44.59
2	Jalingo	76.5	47.41	0.8721	25.51
3	Kaduna	211.65	131.17	0.8833	-34.56
4	Yola	108.8	67.43	0.8920	-23.39
5	Damaturu	78.2	48.464	0.8961	-39.39
6	Maiduguri	73.95	45.83	0.8961	-39.98
7	Gombe	171.7	106.41	0.9000	-37.04
8	Jos	194.65	120.633	0.9112	-32.95
9	Makurdi	68.85	42.67	0.9432	-27.66
10	Aliade	148.89	91.96	0.9469	-26.18

VII. CONCLUSIONS

In this paper, the maximium loadability of weak buses in power system was estimated using PV and QV curves. The Nigeria 330kV transmission network was used a test system modelled in ETAP. The nonlinear PV and QV curves of the ten (10) weakest buses were plotted. The PV and QV curves determined the maximium real and reactive power that can be connected to each bus beyond which the system loose stability. The results shows effectiveness of PV curve and QV curve to determine maximium loadability of weak buses in a power system.

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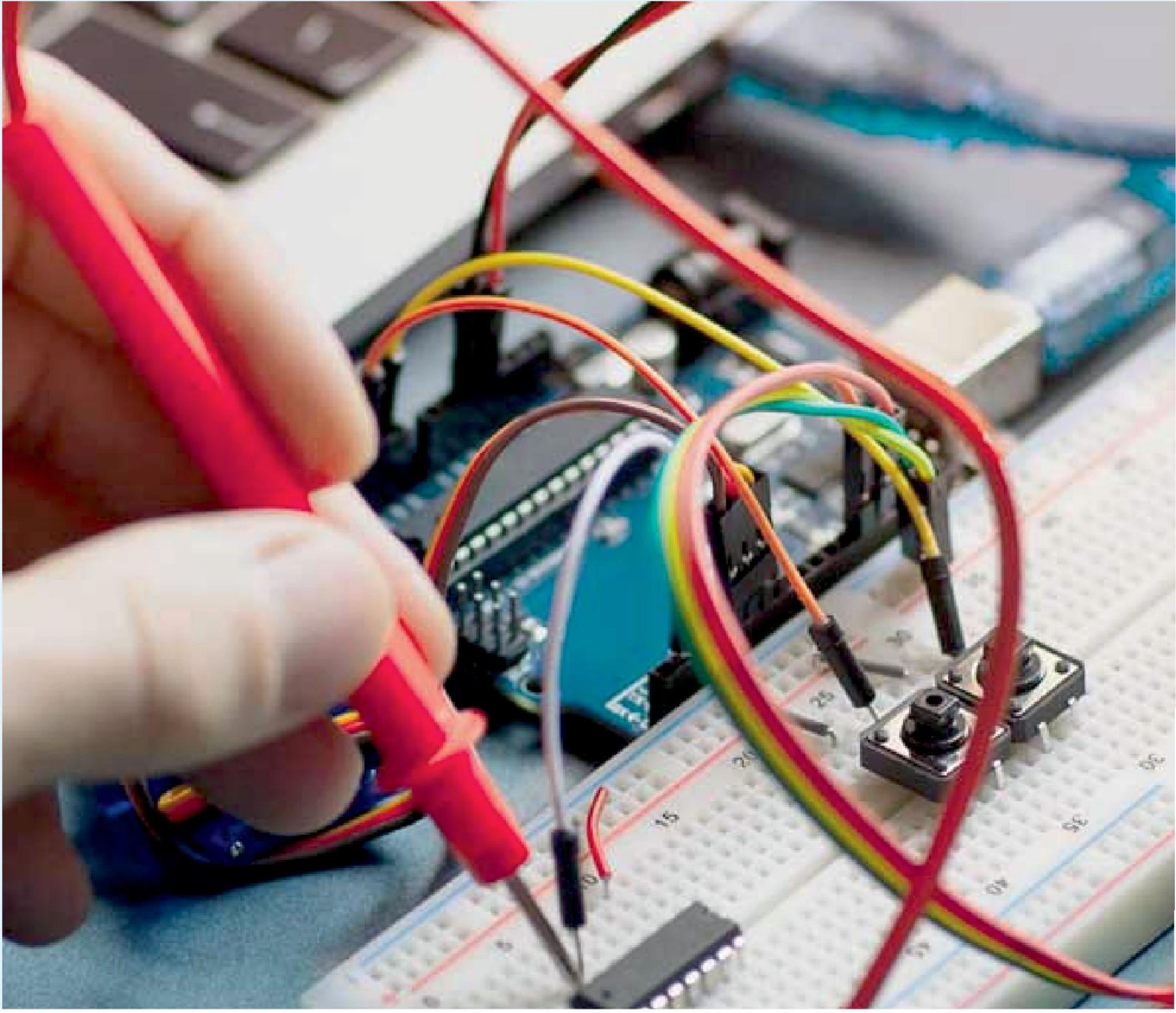

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