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A Quantitative Evaluation of Security Indices for Nigerian National Grid System

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ABSTRACT

Security of a power system is the degree of risk and ability to survive imminent disturbances (contingencies) without interruption of continuous service. Security indices are parametric variables used to represent the degree of operation or malfunction of power system before the system faces interruption of service or the element faces outage or malfunction. A concept opposite to security is vulnerability concept. An element or a system is vulnerable if contingencies lead to an interruption of service at a point or the entire element or system. Vulnerability index (VI) and Margin index (MI) are quantitative security indices that provide comprehensive information about the individual parts and the whole system.

This paper presents a quantitative evaluation of security indices for the Nigerian national grid Mathematical models were formulated for the two prominent security indices. Twenty four generators, Twenty four buses and Twenty four branches were selected as case studies on the Nigerian national grid system while their impacts on the vulnerability and margin indices were stressed. The vulnerability indices increased as more generators were added while the margin indices also decreased proportionately as the number of generators increase. The average value for the vulnerability index was 0.0275 per generator while the average margin index was 0.8073 per generator. The vulnerability indices increased as more buses were added into the system while the margin index between 6 and 7 buses remained constant at 1.0 suggesting that the buses appeared to be at optimum even though, as the number of buses increased, the margin indices decreased. The average vulnerability and margin indices for the buses were 9.921 per bus and 14.0495 per bus respectively. The vulnerability indices for the branches increased with increase in branches while the margin indices decreased as more branches were included in the system. The average vulnerability and margin indices for the branches were 0.1906 and 0.4640 per branch respectively.

The results from this work will assist power system engineers and utility staff in safe-guarding various contingencies emanating from violation of the power system operational limits.
Keywords: Security, Vulnerability Index, Margin Index, Static Security, Dynamic Security, Transient Stability, Contingency.

I. INTRODUCTION

To The security of a power system is its ability to withstand a set of severe but credible contingencies and to survive transition to an acceptable new steady-state condition [2].

It refers to the technical performance and quality of service when a disturbance causes a change in system conditions. This is assessed by detection of operating limit violations and contingency analysis. Security assessment is the process of determining whether a probable contingency will cause the system to enter the emergency state or not [5], [6].

Security assessment can be categorised into static security assessment and dynamic security assessment.

1.1 Static Security Assessment

A static security assessment is usually based on a load flow analysis and deals with steady-state limit violation. Load flow studies are used to ensure that electrical power transfer from generators to consumers through the grid system is stable, reliable and economical. Conventional techniques for solving the load flow problems include iterative, the Newton- Raphson or the Gauss-Siedel methods [7], [11].

The process of obtaining this steady-state condition is known as security monitoring, while the process of obtaining limit violation depicts static security assessment. In addition to steady-state operation of a power system, the power system must be able to survive dynamic events [8],[9].

1.2 Dynamic Security Assessment

Dynamic security assessment is an evaluation of the ability of a certain power system to withstand a defined set of contingencies and to survive the transition to an acceptable steady-state condition [3]. This is dependent on the transient stability evaluation which provides information in relation to the ability of a power system to retain stable operation during major disturbances resulting from either the loss of generation or transmission facilities, sudden or sustained load changes, or monetary faults. In the event of disturbances, the electro-mechanical oscillation of synchronous generator will be used to measure the transient stability. It is determined by observing the variation of the rotor angle as a function of time throughout the duration of the fault [4], [10]. The transient stability depends on the magnitude of the fault, duration of the fault and the speed of the protective device [11]. If the system is transiently stable, the oscillations of the rotor angle will damp down to a safe operating limit. Dynamic security assessment identifies those disturbances that cause instability and the results of the transient stability analysis are used to determine the system's security level [1].

Dynamic security assessment is more computationally intensive as it requires the electro-mechanical transient stability analysis of the system which concerns the transient behaviour of the power system when moving from the pre to the post-contingency operating point [1].

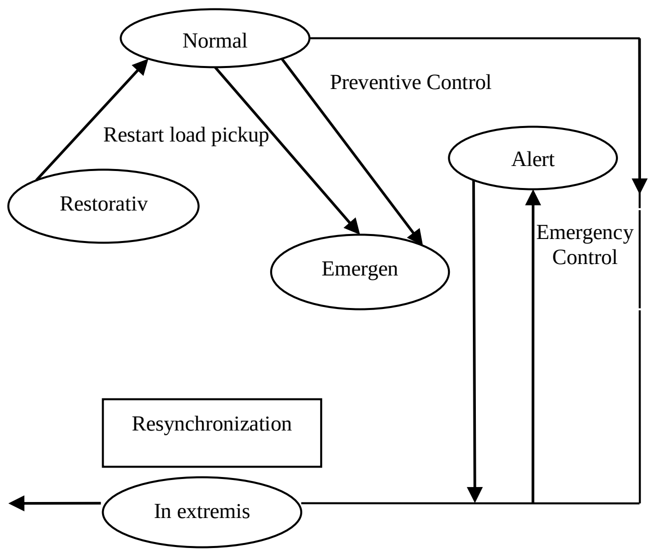

Figure i: State Transition Diagram of a Power system

The operating states of power system are defined as follows:

- i The normal state implies that all system variables are within the normal range and no equipment is overloaded, while all customer demands are met.
- ii In the alert state, the system variables are still within limits and constraints satisfied. However, the system has been weakened to a level where a contingency may cause an overloading of equipment.
- iii If a sufficiently severe disturbance occurs when the system is in alert state, the system on occasion enters the emergency state.
- iv If the control measure initiated at the emergency state should fail, the system will go into the disintegrating sections and all constraints are violated and the system no longer remains intact.
- v The system enters the restorative state if there were any remaining equipment operating within their total capacity or some equipment had been restarted following the total collapse. It is known that an underlying pattern exists to the event that could cause transition from the alert state to the other state. The initiating event could be a disturbance of natural origin, a malfunction of equipment, or a consequence of human factors.

The security condition of the system operation is very essential. They can take some control actions when the system security is being or has been threatened [6], [11]. Vulnerability can be taken as a measure opposite to security. The system is vulnerable if contingencies lead to an interruption of service to a point or the entire system. The element is vulnerable if contingencies or changing conditions lead to violation of the element limit, outage or malfunction of the element [7].

Some indices can be used to represent the degree of vulnerability and security before the power system faces interruption of service or the element faces outage, or malfunction,. Vulnerability index (VI) and margin index (MI) represent comprehensive and quantitative vulnerability and security information of the individual part and whole system [4],[7], [11].

1.3. Line Loadability

This refers to transmission –line voltage decrease when heavily loaded and increase when lightly loaded. When voltages on Extra High Voltage lines are maintained within xxx5% of rated voltage, corresponding to about 10% voltage regulation, unusual operating problems are not encountered. Ten percent voltage regulation for lower voltage lines including transformer voltage drops is also considered good operating practice. In addition to voltage regulation, line loadability is an important issue. The three major line loading limits include: the thermal limit, the voltage-drop limit and the steady-state stability limit. The thermal limit is determined by the maximum temperature of a conductor. The loadability of short transmission lines is usually determined by the voltage-drop limit.

II. METHODS AND MATERIAL

Model Development

Consider a power system with 'm' generators, 'n' buses and 'p' branches.
The Vulnerability Index (VI) and Margin Index (MI) are defined as:

(a) For Generators:

Vulnerability index and margin index are expressed as

$$VI_{Pgi} = \frac{W_{Pgi}}{2N}\left({Pg_i}/{Pg_{imax}} \right)^{2N} \quad (1)$$

$$VI_{Qg} = \frac{W_{Qg}}{2N}\left({Qg_i}/{Qg_{imax}} \right)^{2N} \quad (2)$$

$$VI_{gen,loss\ i} = W_{gen,loss\ i} k_{gen,loss\ i} \quad (3)$$

$$VI_{gen} = \sum_{i=1}^{m}\left(VI_{Pgi} + VI_{Qgi} + VI_{gen,loss\ i}\right) \quad (4)$$

$$MI_{Pgi} = I - \frac{P_{gi}}{P_{gimax}} \quad (5)$$

$$MI_{Qgi} = I - \frac{Q_{gi}}{Q_{gimax}} \quad (6)$$

(b) For buses: vulnerability index and margin index are expressed as

$$VI_{vi} = \frac{W_{vi}}{2N}\left(V_i - {V_i^{sche}}/{\Delta V_{i,lim}} \right)^{2N} \quad (7)$$

$$VI_{loadabi} = \frac{W_{loadabi}}{2N}(V_{loadabi})^{2N} \quad (8)$$

$$VI_{load-loss} = W_{load,lossi} k_{load,lossi} \quad (9)$$

$$VI_{bus} = \sum_{i=1}^{m}(VI_{vi} + VI_{loadabi} + VI_{load-loss}) \quad (10)$$

$$MI_{v,i} = I - \left| \frac{V_i - V_i^{sche}}{\Delta V_{ilim}} \right| \quad (11)$$

$$MI_{loadabi} = I - r_{loadabi} \quad (12)$$

(c) For branches, vulnerability index and margin index are expressed as

$$VI_{Pf_i} = \frac{W_{Pf_i}}{2N}\left({Pf_i}/{S_{imax}} \right)^{2N} \quad (13)$$

$$VI_{Qf_i} = \frac{W_{Qf_i}}{2N}\left(Qf_i/S_{imax}\right)^{2N} \quad (14)$$

$$VI_{Qc_i} = \frac{W_{Qc_i}}{2N}\left(Qc_i/S_{\Sigma}\right)^{2N} \quad (15)$$

$$VI_{line,anglei} = \frac{W_{line,anglei}}{2N}\left(L_{ai}b/L_{aimax}\right)^{2N} \quad (16)$$

$$VI_{Relayi} = \frac{W_{Relayi}}{2N}\left(\left(I/d_{sr,i}\right)^{2N} + \left(I/d_{rsi}\right)\right) \quad (17)$$

$$VI_{line,linei} = W_{line,lossi}k_{linelossr} \quad (18)$$

$$VI_{line} = \sum_{i=1}^{p}\left(VI_{Pfi} + VI_{Qfi} + VI_{line,anglei} + VI_{Relayi} + VI_{lineoffi}\right) \quad (19)$$

$$MI_{sfi} = I - \frac{S_{fi}}{s_{imax}} \quad (20)$$

$$MI_{line,anglei} = I - \frac{L_{ai}}{L_{imax}} \quad (21)$$

$$MI_{Relayi,sr} = d_{sri} - K_{zi.sr}\left|\sin\left(\frac{\pi}{2} - \alpha_i + \theta_{d.sr}\right)\right| \quad (22)$$

$$MI_{Relayi,rs} = d_{rsi} - K_{zi.rs}\left|\sin\left(\frac{\pi}{2} - \alpha_i + \theta_{d.rs}\right)\right| \quad (23)$$

where:

VI_{xx} = vulnerability index for different parameters,
xx = P_g, Q_g, gen-loss etc,
MI_{xx}= margin index for different parameters,
W_{xx}= weighting factor for different parameters,
$K_{xlossi} - 0$= no loss,
I= complete loss,
$0 - 1$= loss ratio,
x= gen, load, line,
N = 1 in general,
$r_{load\ ab\ i}$= bus i loadability,

$$r_{load\ ab-i} = \frac{Z_{th.i}}{Z_{Li}}$$

Z_{th}= thevenin equivalent system impedance seen from bus i,

Z_{Li} = equivalent load impedance at bus i at steady state,

P_f, Q_f, S_f = real, reactive and apparent power of line i,

Q_{ci}= linei charging,

Q_{Σ} = the total reactive power input of all generators or total reactive power supply of the whole system.

$MI_{Relay\ i}$ = distance from the apparent impedance seen by the transmission line.

III. RESULT AND DISCUSSION

A. Effect of Generators on Vulnerability Index and Margin Index.

The initial real power increased as the number of generator increased. For 3 generators, the initial real power was 0.81.kW. The initial real power for 1 generator was 0.75 kW while that of 50 generators was 5.10 kW indicating that the more the number of generators, the more the initial real power in the system as illustrated in Figure 1.This is due to the fact that the initial real power and the number of generators are linearly related. Figure 2 illustrates the variation of final real power with the number of generators. The final real power was constant for different number of generators because the generators appeared to have attained their peak values/operational limits at this instance. The final real power was 12.30 kW for 5 generators and also 12.38kW for 50 generators.

The variation of real power ratios with the number of generators is also illustrated in Figure 3.The ratio of initial real power to the final real power with the number of generators decreased as more generators were added to the system because the generators varied linearly as the initial real power. Thus, for 7 generators, the ratio of the initial real power to the final real power was 0.0840 kW and for 40 generators, the ratio was 0.2771 kW. Figure 4 shows the variation of the vulnerability index with the number of generator. The vulnerability index increased as more generators were added to the system because the index depends majorly on the initial real power. Thus, when there were 6 generators, the vulnerability index was 0.0038 and for 30 generators, the index was 0.0247.

The Margin index varied with the number of generators as shown in Figure 5. The margin index decreased as more generators were added, even though, at constant final real power, the initial real power increased as more generators were added into the system. Thus, for 24 generators, margin index was 0.8253 and for 38 generators, the index was 0.7488. Figure 6 expresses how the vulnerability indices and margin indices varied with the number of generators. The vulnerability index increased as more generators were added. The margin index also increased as more generators were added into the system mainly because as more generators were added, the initial real power increased proportionately. Thus for 18 generators, the vulnerability and margin indices were 0.0117 and 0.8603 respectively.

The vulnerability indices varied with the margin indices as shown in Figure 7. As the number of generators increased, the vulnerability index increased. The margin index decreased appropriately because the initial real power decreases proportionately as more generators were added even though, the final real powers remained constant throughout at 12.38 W.

B. Effect of Buses on Vulnerability Indices and Margin Indices.

Figure 8 shows the relationship between the bus loadability and the bus number. The more the number of buses, the more loaded the buses are. In this case, the bus loadability increasedas the number of buses increased.This is because the loading of the buses depends to a larger extent on the number of buses in the system. For 10 buses, the bus loadabilitywas 7.6 while for 30 buses, the bus loadability was 0.71. The initial bus varied with the buses as illustrated in Figure 9. The bus voltage at the output increasedas the number of buses increased. Thus, for 2 buses, the initial bus voltage was 1.6 V and for 12 buses, the initial bus voltage was 4.7 V. The bus voltage at start increased as more buses were added to the system.

The relationship between the final bus voltage and the bus number is shown in Figure 10. The final bus voltage increasedas the number of buses increased. Thus, at a final bus voltage of 10.1 V, there were 14 buses and at 23 buses, the final bus voltage increased proportionately to 17.1 V. This trend is followed throughout the study period. Figure 11 illustrates the variation of the absolute value of change in bus voltage with the buses. The change in bus voltage increased as more buses were added to the system. Thus when the absolute value of change in bus voltage was 0.6 V, there were 4 buses and at 12 bus, the change in bus voltage had increased to 3.1 V.

The correlation between the vulnerability index and buses is shown in Figure 12. The vulnerability index increased as more buses were added into the system because the vulnerability index varied inversely as the number of buses. For 10 buses, the vulnerability index was 23.10 while for 18 buses, the vulnerability index was 7.40. Figure 13 shows how the absolute value of change in bus voltage varied with the buses, the absolute value of the change in bus voltage increased as more buses were added and vice versa because the initial and final bus voltages increased as more buses were introduced into the system. The variation of vulnerability index with margin index is shown in Figure 14. At 6 buses, the vulnerability and margin indices are 33.86 and 1.0 respectively. Between 6 and 7 buses, the margin indices are 1.0 and 1.0 respectively suggesting that the buses appeared to be at optimum here even though, as the number of buses increased, the margin indices decreased as well with corresponding increase in the vulnerability indices.

C. Effect of Branches on Vulnerability Indices and Margin Indices.

Figure 15 shows the relationship between the final reactive power and the branches. Observation shows that the final reactive power increased as more branches were introduced in to the system because more branches indicated the need to have more final real power into the system. Thus, with 10 branches, the final reactive power was 1.29 kVAR and for 20 branches, the final reactive power increased to 1.81kVAR. The least and highest final reactive powers were 0.8 kVAR and 3.61 kVAR respectively corresponding to 1 and 50 branches respectively. The maximum reactive power varied with the braches as illustrated in Figure 16. The final reactive power increased as more branches were present in the system and vice-versa. The least final reactive power for the branches was 0.8 kVAR and the highest final reactive power for 50 buses was 3.80kVAR.

Figure 17 shows how the reactive power ratio varied with the branches. The ratio of the reactive powers increased due to the fact that both the initial and final reactive powers increased as more branches were introduced into the system. Thus, the least reactive power ratio of 0.6950 corresponds to ‘1’ branch and the highest real power ratio of 0.4311 corresponds to ‘24’ branches. The variations of the reactive power (both initial and final) with the branches are illustrated in Figure 18. Both the initial and final powers varied linearly with the branches because the initial and reactive powers increased as more branches were introduced into the system.

Figure 19 shows the variation of vulnerability index with the branches. This index increased as more branches were introduced. This is because more real power were required in the system. For 10 branches, the vulnerability index was 0.1624 while this index increased to 0.2221 for 24 branches. The least and highest vulnerability indices for 1 and 24 branches are 0.1211 and 0.2221 respectively confirming the assertion that the vulnerability index increased as the number of branches increased and vice-versa. The variation of the margin index with the branches is illustrated in Figure 20. The margin indices for 5, 10, 15 and 20 branches are 0.5906, 0.5838, 0.5701 and 0.5110 respectively indicating reduction in margin indices as the number of branches increased.

Figure 21 illustrates the variation of the vulnerability index with the margin index. The vulnerability indices increased with the increase in the number of branches while the margin indices decrease proportionately as the numbers of branches reduce. Thus, as the vulnerability indices increased, the margin indices decreased proportionately as the number of branches increased.

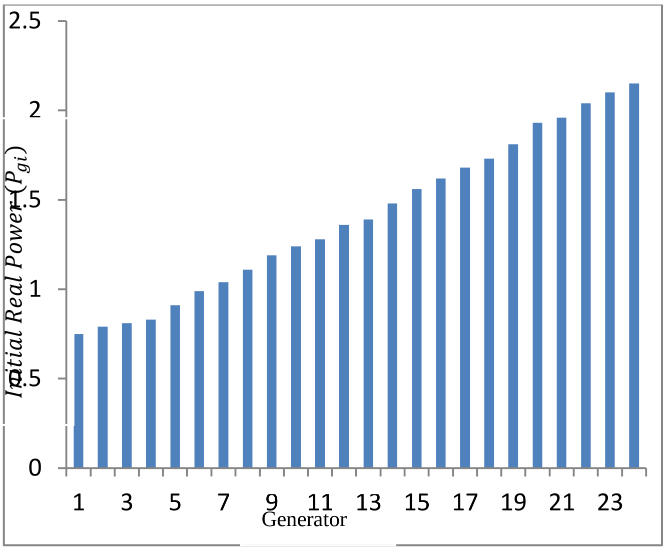

Figure 1: Initial Real Power versus Number of Generator

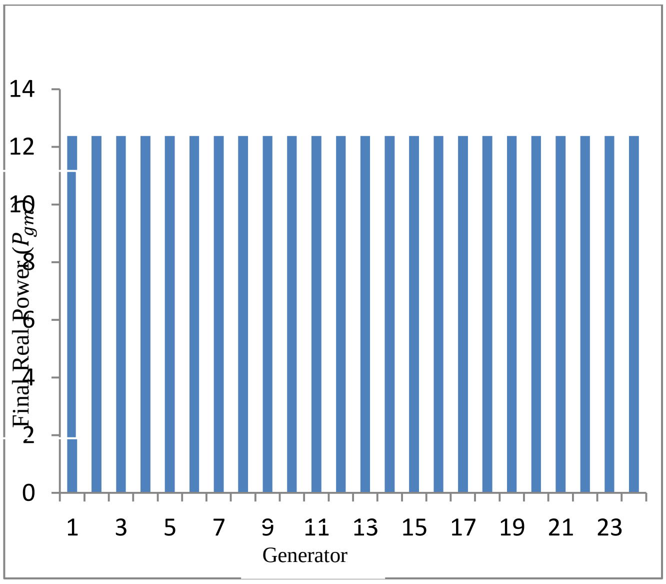

Figure 2: Final Real Power versus Number of Generator

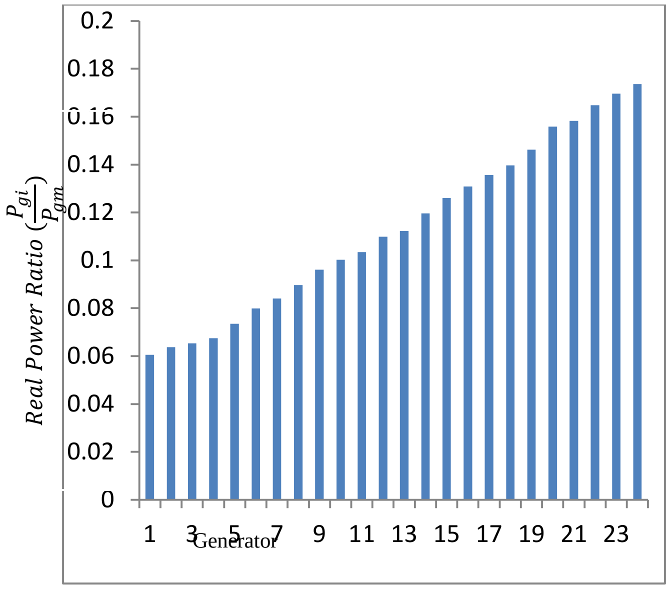

Figure 3: Ratio of Initial Real Power to Final Real Power versus Number of Generator.

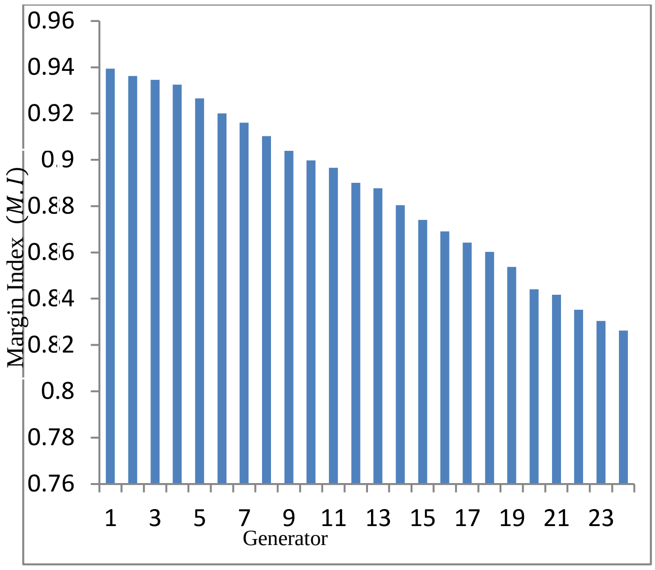

Figure 5: Variation of Margin Index with Generator

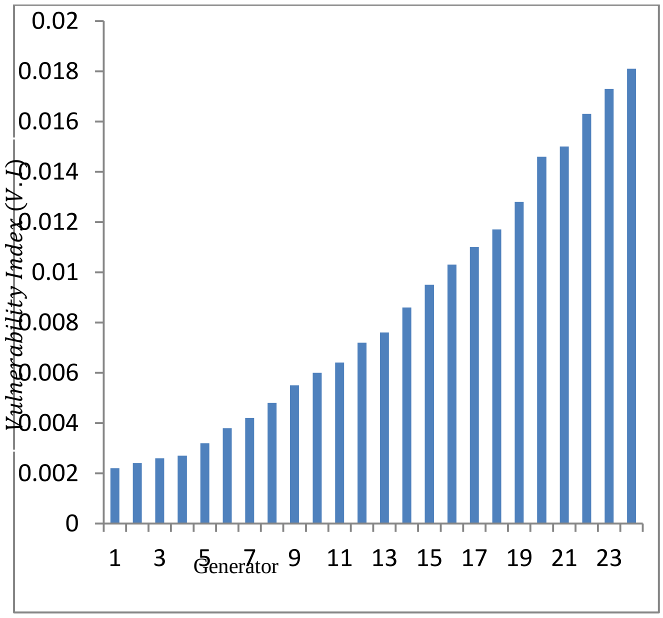

Figure 4: Variation of Vulnerability Index with Generator

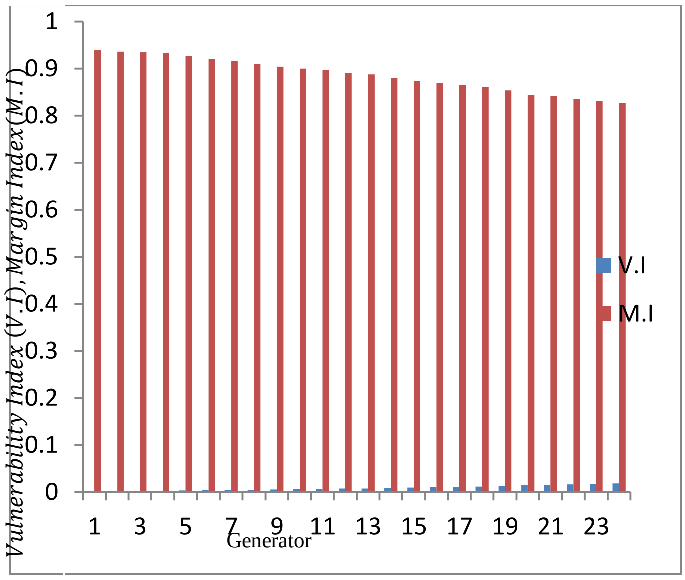

Figure 6: Variation of Vulnerability index and Margin Index versus Generator.

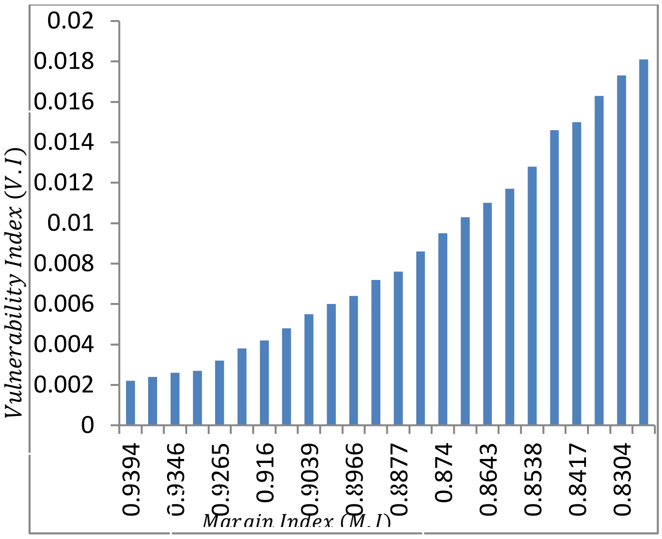

Figure 7: Variation of Vulnerability Index with Margin Index.

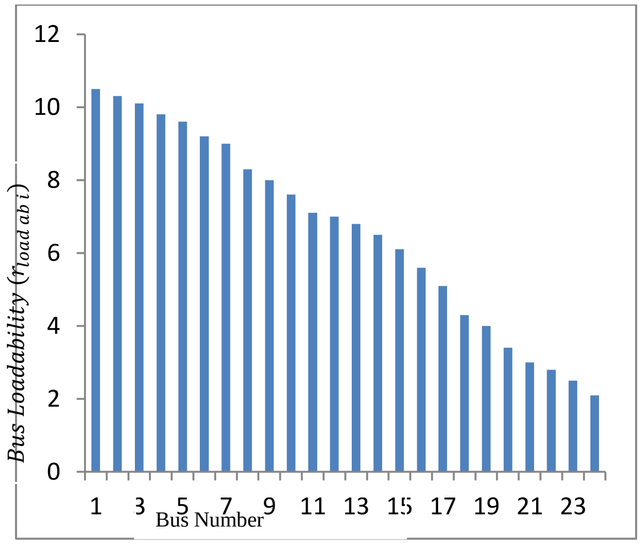

Figure 8: Variation of Bus Loadability with Bus number.

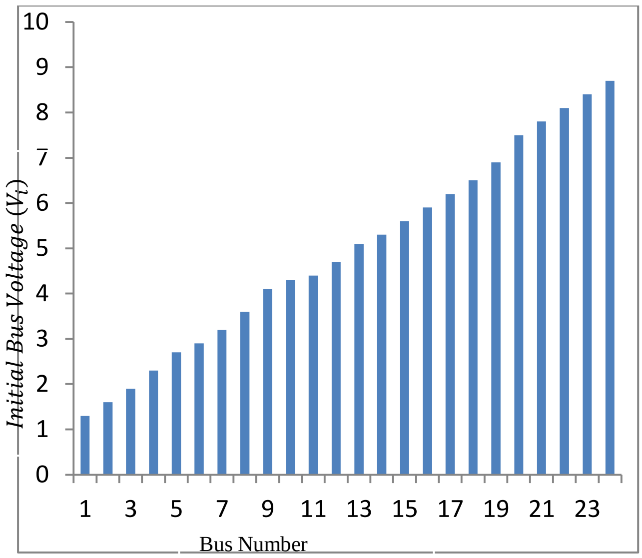

Figure 9: Variation of Initial Bus Voltage with Buses.

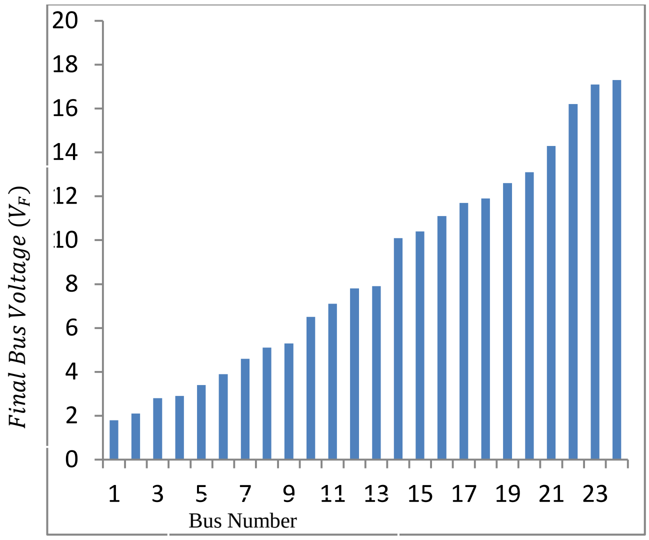

Figure 10: Variation of Final Bus Voltage with Buses.

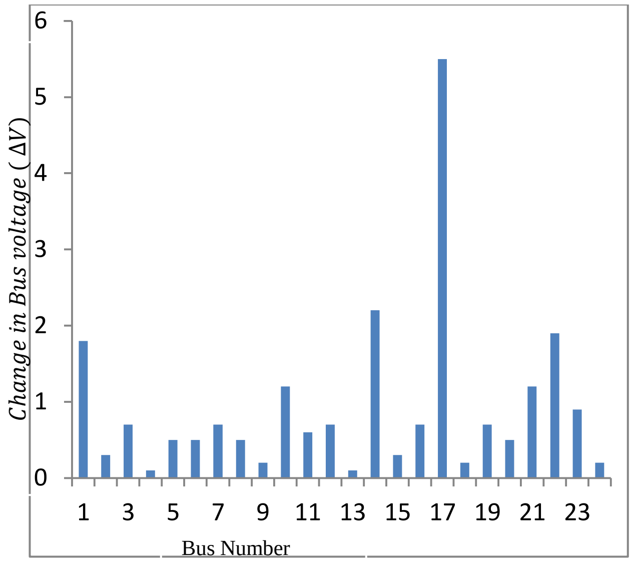

Figure 11: Change in Bus Voltage versus Buses.

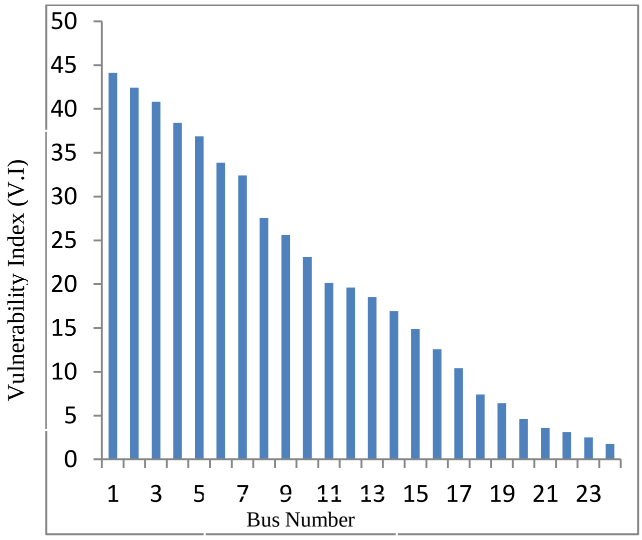

Figure 12: Variation of Vulnerability Index with Buses.

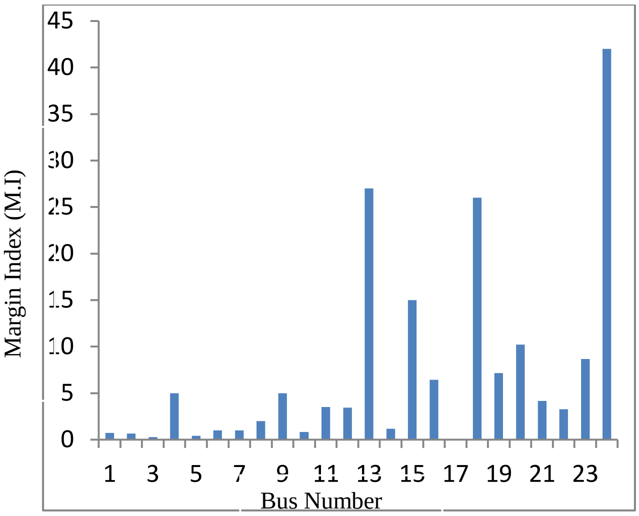

Figure 13: Variation of Margin Index with Buses.

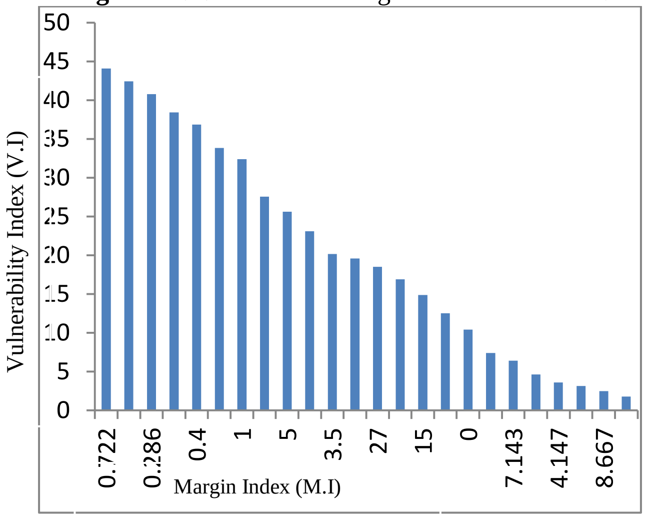

Figure 14: Variation of Vulnerability Index with Margin Index.

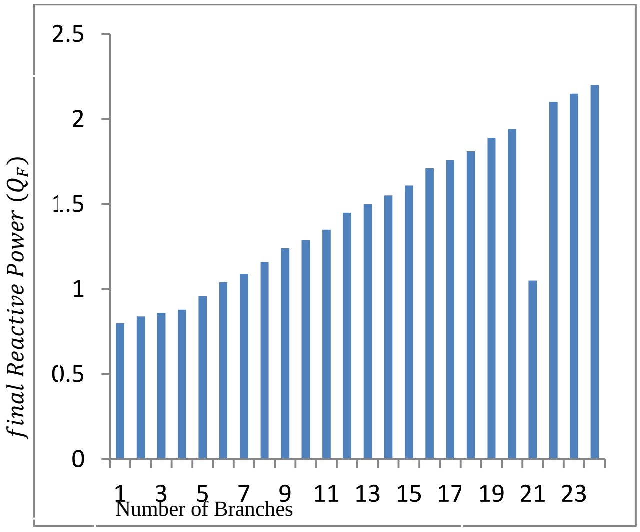

Figure 15: Final Reactive Power versus Branches

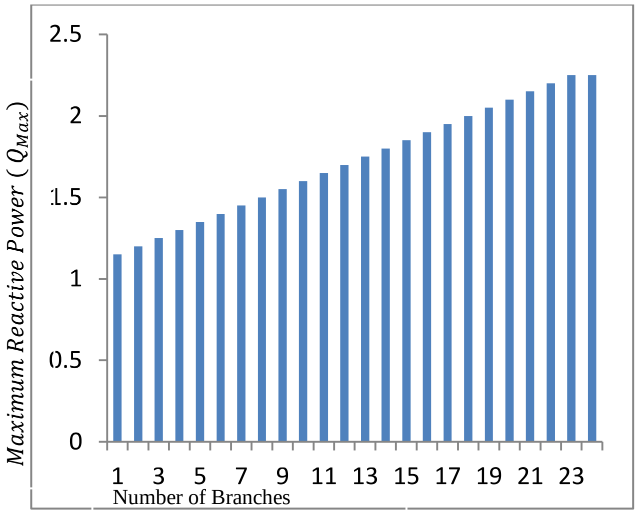

Figure 16: Maximum Reactive Power versus Branches

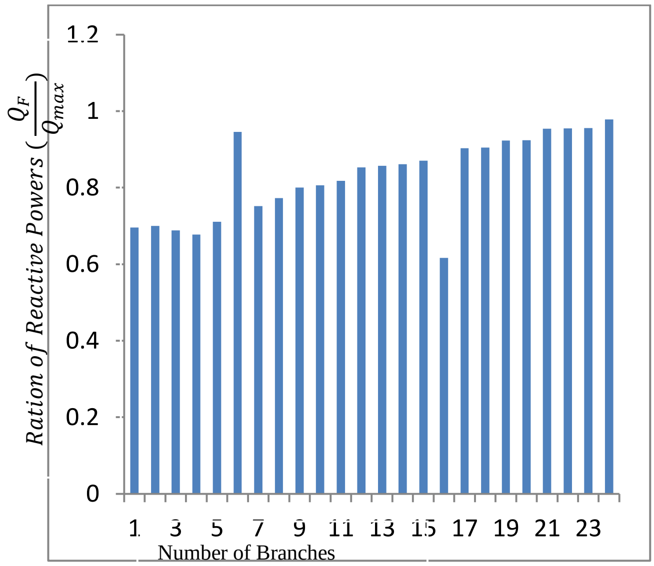

Figure 17: Ratios of Reactive Powers versus Branches

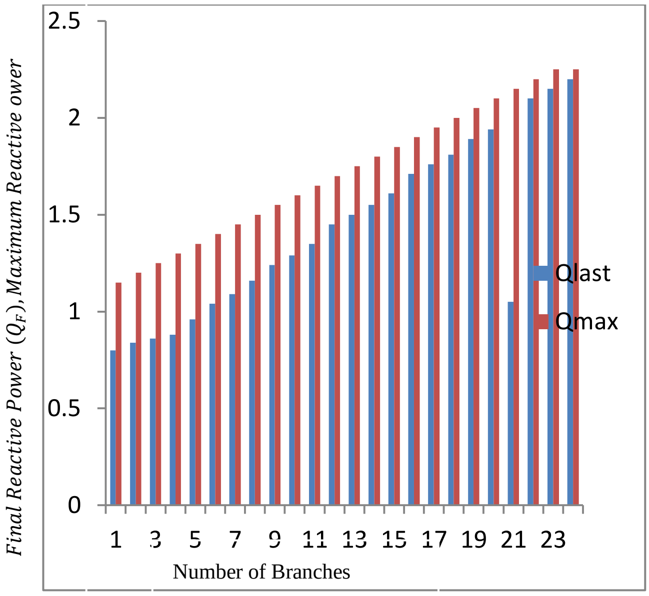

Figure 18: Variation of Final Reactive Power and Maximum Reactive Power with branches

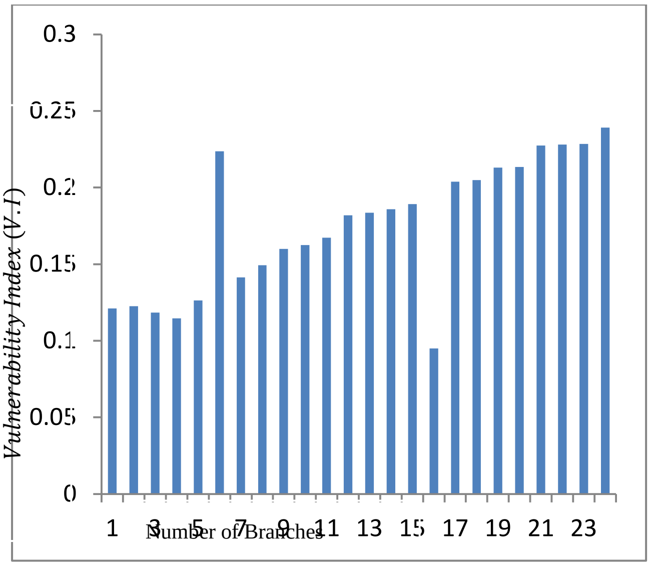

Figure 19: Variation of Vulnerability index with Branches

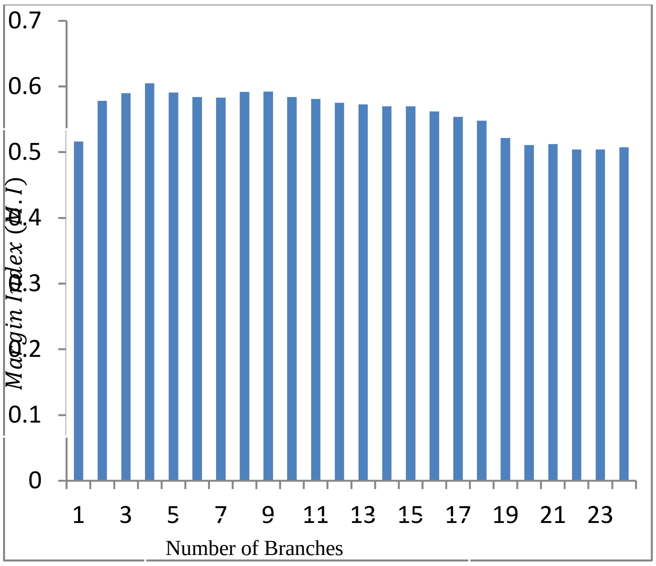

Figure 20: Variation of Margin index with Branches

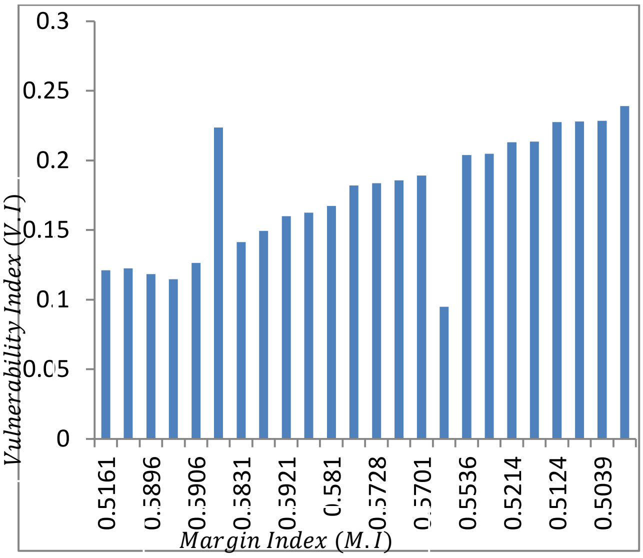

Figure 21: Variation of Vulnerability index with Margin index

IV. CONCLUSION

A quantitative assessment of security indices for the Nigerian national grid system has been presented. Twenty four generators, twenty four buses and twenty four branches were selected on the Nigerian national grid system as case studies while their impacts on the vulnerability and margin indices were stressed. The vulnerability indices increased as more generators were added while the margin indices also decreased proportionately as the number of generators increased. The average value for the vulnerability index was 0.0275 per generator while the average margin index was0.8073 per generator. The vulnerability indices increased as more buses were added into the system while the margin index between 6 and 7 buses remained constant at 1.0 suggesting that the buses appeared to be at optimum even though, as the number of buses increased, the margin indices decreased. The average vulnerability and margin indices for the buses were 9.921 per bus and 14.0495 per bus respectively. The vulnerability for the branches increased with increase in branches while the margin indices decreased as more branches were included in the system. The average vulnerability and margin indices for the branches were 0.1906 and 0.4640 per branch respectively.

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