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Assessment and Prediction of Voltage Collapse on Nigerian Power System

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ABSTRACT
A large integrated of transmission lines that connectedgenerators and load is refers to electric power system. Major problem confronting the efficient power system is voltage collapse due to heavily loaded lines and reactive power shortage. This paper therefore, focused on assessment and prediction of voltage collapse on Nigerian power system.Newton-Raphson (NR) power flow analysis was performed for contingency. Voltage Stability Prediction Index (VSPI) was calculated to detect voltage collapse point. Firefly Algorithm (FA) was utilized to optimize the solution and simulation was carried out using MATLAB R(2018b). The performance of the approach was tested on Nigerian 28-bus power system. Results indicated that buses 6 and 16 with voltage magnitude and VSPI values of 1.0000 p.u and 0.2433; 1.0000 p.u and 0.3332, respectively, were buses for best location of compensation devices for preventing voltage collapse in the power system. Thus, the usage of FA gave a better optimum solutionfor voltage collapse prediction point in power system.

Keywords: *Electric Power System, Firefly Algorithm, Voltage collapse, Voltage Stability Prediction Index, Reactive Load Capacity, Voltage Magnitude..*

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I. INTRODUCTION

The Nigerian power systems have undergoing numerous changes and becoming more complex from operation, control and stability maintenance standpoints due to high demand of electricity as a results of improve economic activities of the people [1]. The most usual practice in power system is an interconnected network of transmission lines that links generators and loads in which the generating stations located thousands of kilometers apart, operate and transmit electricity to load centers [2, 3].

However, improper planning, construction, operation and control of the power system increase the complexity problem of an interconnected power system [2]. Thus, the major problem confronting the efficient performance of an interconnected power system network is voltage collapse. Many recent power system blackouts have been the consequences of instabilities characterized by sudden voltage collapse phenomena [3-5].

A power system is said to enter a state of voltage collapse when a disturbance causes a progressive and uncontrollable decline in voltage, as a result of the inability of the network to meet the increased demand for reactive power. The voltage decline is monitored at the beginning of the collapse and difficult to detect. A sudden increase in the voltage decline leads to the end of the collapse scenario [4, 6, 7].

Furthermore, voltage collapse contributes to large extent of electricity blackouts and it is the major concerns for today's power system engineers [6]. Its occurrence is limited in developed countries despite their complex networks but its frequency is high in Nigeria. This is due to the fact that the Nigerian national grid is old and weak, highly stressed and hence lacking flexibility [1, 5].

This inefficient supply of electricity has led to the closure of both small business and large industries in the country which have made business organization wary of investing in the country economy. It has reported that the rate of voltage collapse on Nigerian power system is very high [4,8].

Therefore, voltage collapse assessment on Nigerian power system is very important in determining the system operating limits and operating guidelines of power system. The analysis would also establish the power supply system's reliability and ability to withstand different disturbances. In addition, engaging adequate provision of regular, affordable and efficient electricity supply would attract more industrialization.

II. RELETED WORKS

According to Ajenikoko *et al.,* (2019), National Electric Power Authority (NEPA) and Power Holding Company of Nigeria (PHCN) has been sole proprietors of Nigerian power systemuntil 2013 when it was handed over to eighteen successor companies made up of generation, electricity transmission and distribution companies [8]. Also, Kiran *et al.,* (2016) and Ajenikoko, (2018) explained that, there are 77 grid-connected generating plants in operation in the Nigerian Electricity Supply Industry (NESI).The total installed capacity of the power system is 12, 800 MW and available capacity is 7,139.6 MW, in which the thermal generator station accounted for 86 % of total capacity while the hydro-based stations accounts for 1,938.4 MW of total installed capacity [3, 9].

Furthermore, Oluseyi *et al.,* (2015) and Ogbuefi *et al.,* (2017) explained that the recurrent power outages across the Nigeria is has a results of the fluctuation in power generated which average range between 1,500 MW and 5,000 MW which is inadequate when compared to the 10,000 MW of energy demanded by the millions of consumers craving for electricity in the nation [10, 11].On the other hand, the transmission network in Nigeria currently has the capacity to transmit a maximum of about 4,000MW [9, 12, 13].

The Nigeria power system is currently suffering from inadequate generation and transmission capacity. The transmission network is not sufficient to transfer the additional power injected to the grid by the new power plants due to their radial connection.These issues on the Nigeria power system has negative impact which has held back the efficiency of evacuating power generated in the country [1, 2, 9, 14, 15].

Furthermore, Nigeria power system is characterized by very lengthy transmission lines which make voltage control difficult. This has reduced the margin between the planned power transfer and the maximum limit at which the lines is susceptible to transient and dynamic instability [14]. Furthermore, the structure of the Nigerian power grid system is weak due to the existence of several single lengthy radial transmission lines duplicated lines, thus vulnerable to voltage collapse. In other to avoid these collapses, there is the need to carry out maintenance at least once every forty-one days along the transmission line [9, 12, 13].

In view of this, it is very essential to study the voltage collapse on the Nigerian power grid system in order to know the system disturbances that are responsible for the high system collapse and then proffer focused solutions to reduce the system collapse on the power grid.

Adesina *et al.,* (2019) explained that voltage collapse is a consequential effect of voltage instability which is the process by which voltage falls to a very low value as a result of series of events in a power system [16]. Many large interconnected power systems are increasingly experiencing voltage collapse whichposes a primary threat to power system stability, security and reliability. Excessive voltage decline can occur following some severe system contingencies and this situation could be aggravated, possibly leading to voltage collapse due to overloading [17, 18].

Ogbuefi *et al.,* (2017) showed that power systems have evolved through continuing growth in interconnections resulting in more complexity and highly stressed operation conditions. This has given rise to different forms of voltage collapse [11]. Thus, the consequences of voltage collapse on power system are; low voltage profiles, heavy reactive flows, inadequate reactive support and heavily loaded systems. The voltage collapse is often precipitated by low probability of single or multiple contingencies [7, 12].

According to Anwar and Tanmoy, (2014) and McMillin *et al.,* (2015) heavy loading of the power system is one of the major reasons of voltage collapse in power system. The system appears unable to supply the reactive power demand. Producing the demanded reactive power through synchronous generators, static capacitors can solve the problem. Another solution is to build transmission lines to the weakest nodes [19, 20].

A. Newton-Raphson load flow method

Load flow analysis is very crucial for all calculations relating to the power network since it concerns the power network performance in its steady-state operating conditions [21, 22, 23]. The most commonly used iterative methods for solving optimal load flow analysis problems is the Newton-Raphson (NR). The iterative method is majorly useful for large network and has moderate compute storage requirements [15, 19, 21].

In this method, initial guesses of all unknown variables were inputted. With the higher order terms ignored, a Taylor's series is written for each of the power balance equations [24]. The Jacobian matrix is formed by neglecting all higher order terms..The process continues until a stopping condition is met. A common stopping condition is to terminate if the norm of the mismatch equations are below a specified tolerance [2, 24]. Thus, for a typical bus of the power system, the equation for NR iterative method is given below [8]:
The current of the power system polar form is given as:

$$I_i = \sum_{j=1}^{n} \left|Y_{ij}\right|\left|V_j\right| \angle \theta_{ij} + \delta_j \qquad (1)$$

The real and imaginary parts are given as:

$$P_i = \sum_{j=i} |V_i||V_j||Y_{ij}| Cos\left(\theta_{lj} - \delta_i + \delta_j\right) \qquad (2)$$

$$Q_i = -\sum_{j=i} |V_i||V_j||Y_{ij}| Sin\left(\theta_{ij} - \delta_i - \delta_j\right) \qquad (3)$$

The linear Equation of the Jacobian matrix is [25, 26]:

$$\left[\begin{array}{c} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{array}\right] = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial V_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial V_n} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial V_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial V_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial V_n} \end{array}\right] \left[\begin{array}{c} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta\left|V_2^{(k)}\right| \\ \vdots \\ \Delta\left|V_n^{(k)}\right| \end{array}\right] \qquad (4)$$

The elements of the Jacobian matrix are the partial derivatives of (2) and (3), evaluatedas:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad (5)$$

J is a matrix of partial derivatives known as a Jacobian

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial |V_i|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial |V_i|} \end{bmatrix} \quad (6)$$

The power residuals, given as;

$$\Delta P_i^{(k)} = P_i^{(sch)} - P_i^{(k)} \qquad (7)$$

$$\Delta Q_i^{(k)} = Q_i^{(sch)} - Q_i^{(k)} \qquad (8)$$

The new estimates for phase angle and bus voltages are:

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \qquad (9)$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \qquad (10)$$

where; ΔP and ΔQ are called the mismatch or residual, I_i is current at bus I, Y_{ij} is mutual admittance between buses i and j, $V_i and V_j$ calculated voltage of bus i and j, $\theta_{ij}$is phase angle at bus i and j, $\delta_i^{(k)}$is the calculated angle, $\Delta\delta_i^{(k)}$is the change in calculated angle.

B. Firefly Algorithm Method

Firefly Algorithm (FA) is a nature inspired meta-heuristic algorithms which is inspired by the flashing behavior of fireflies and the phenomenon of bioluminescent communication [27, 28].The algorithm works based on global communications among the fireflies and can find global and local optimal simultaneously [29].

The Firefly Algorithm has three particular idealized rules [27, 29]:

i. Fireflies are unisex,move towards more attractive and brighter ones.
ii. The degree of attractiveness is proportional to its brightness
iii. The brightness or light intensity of a firefly is determined by the value of the objective function of a given problem.

In each step, the FA computes the brightness and attractiveness of each firefly and the positions of the fireflies are updated based on the value. After enough number of iterations, all fireflies would converge to the best possible position on the search space [28].There are two important issues used in the application of FA: the variation of light intensity and formulation of the attractiveness. Furthermore, for a given medium with a fixed light absorption coefficient ‘γ’, the form of attractiveness function of a firefly is given as [28, 30]:

$$\beta_r = \beta_0 * \exp\left(-\gamma r_{ij}^m\right) \quad \text{with } m \geq 1 \qquad (11)$$

The distance between any two fireflies is given as [27, 30]:

$$r_{ij} = \left\|x_i - x_j\right\| = \sqrt{\sum_{k=1}^{d}\left(x_{i,k} - x_{j,k}\right)^2} \qquad (12)$$

for *d=2,*Equation (2.64) becomes:

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{13}$$

The movement of a firefly i which is attracted by a more attractive firefly j is given as:

$$x_{i+1}= x_i + \beta_0 * \exp\left(-\gamma r_{ij}^2\right) * \left(x_j - x_i\right) + \alpha * \left(rand - \frac{1}{2}\right) \tag{14}$$

where; r is the distance between any two fireflies, β_0 is the initial attractiveness γ is an absorption coefficient, *d*is the number of distance, α is a randomizationparameter, *rand* is a random number generator..

III. METHODOLOGY

In this paper, a Voltage Stability Prediction Index (VSPI) was calculated for detection of voltage collapse point with testing data from base case and contingency. NR load flow analysiswas performed to solve the linearized power flow equations of VSPI. Firefly Algorithm (FA) was employed as optimal stability technique to determine optimum voltage collapse point. This was doneto give the global optimal solutions for power system stability.The maximum load-ability of the system was identified and critical lines were ranked.The effectiveness of FA for voltage collapse analysis was implemented on Nigerian 28-bus transmission system shown in Figure 1.

The system has 60 transmission line circuits, 9 effective generation stations, 19 load stations and 52 transmission lines. The entire grid system is sectioned into North, South-East and the South-West geographical zones [2, 15]..

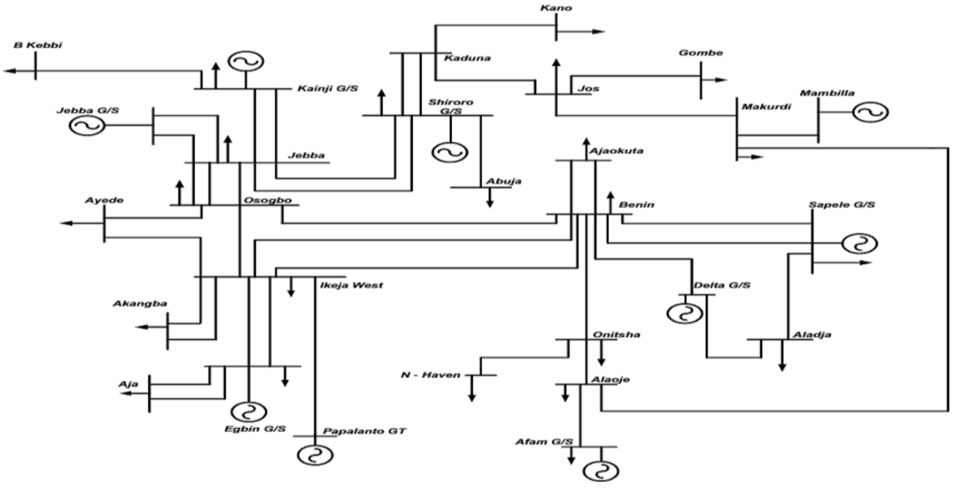

Figure 1: Nigerian 330 kV, 28 –Bus Network

A. Problem Formulation

To maintain stable operations, especially during disturbances is one of serious challenges facing power system operator. During analysis of voltage stability, determinationof voltage collapse point is very necessary in planning and operation of power system. This helpto identify load buses with high impact of voltage instability or collapseand the required generation reduction to maintain power balance within prescribed maximum and minimum allowable values. Hence, the objective function to be minimized is given as [7]:

$$f = \min\left(VSI\right) \tag{15}$$

$$VSI = \min\left(\frac{P_{\max} - P_r}{P_{\max}}, \frac{Q_{\max} - Q_r}{Q_{\max}}, \frac{S_{\max} - S_r}{S_{\max}}\right) \tag{16}$$

where;

$$P_{\max} = \sqrt{\frac{V_s^4}{4X} - Q_r \frac{V_s^2}{X}} \tag{17}$$

$$Q_{\max} = \frac{V_s^2}{4X} - \frac{P_r^2 X}{V_s^2} \tag{17}$$

$$S_{\max} = \frac{(1 - Sin\theta)V_s^2}{2Cos^2\theta \cdot X} \qquad (18)$$

where; f is the objective function, VSI is the Voltage Stability Index of line overloads, $P_{\max}$ is the maximum real power, $Q_{\max}$ is the maximum reactive power, $S_{\max}$ is the maximum apparent power

The minimization problem is subject to the following constraints:

Equality Constraints:

$$P_{Gi} - P_{Di} - \sum_{i=1}^{N} |V_i||V_j||Y_{ij}| Cos(\theta_{ij} - \delta_i + \delta_j) \qquad (19)$$

$$Q_{Gi} - Q_{Di} - \sum_{i=1}^{N} |V_i||V_j||Y_{ij}| Sin(\theta_{ij} - \delta_i + \delta_j) = 0 \qquad (20)$$

Generation constraints:

$$P_{Gi}^{Min} \le P_{Gi} \le P_{Gi}^{Max} \; i = 1, ..., NG \qquad (21)$$

$$Q_{Gi}^{Min} \le Q_{Gi} \le Q_{Gi}^{Max} \; i = 1, ..., NG \qquad (22)$$

Load bus constraints:

$$V_{Li}^{Min} \le V_{Li} \le V_{Li}^{Max} \; i = 1, ..., NL \quad (23)$$

where, *NL* is the number of load buses.where; *NG* is the number of generators.

B Simulation for Stability Analysis

The simulation for NRload flow for stability for base case and with contingency was carried out in MATLAB R(2018b) according to the following:

Step 1: The system data and parameters were input;
Step 2: The load flow at a given steady stateand contingency were performed;
Step 3: The admittance matrix were formed
Step 4: Linearize equation of the system and solve all elements of the Jacobian matrix directly;
Step 5: The convergence was checked and the Jacobian matrix was modified, else go to step 2;
Step 6: The VSPI of the system is calculated using Equation (24);

$$VSPI = \frac{4Q_r}{|V_s|^2} \left[a\frac{Z^2}{X} - (a-1)\frac{1}{Sin^2(\theta - \delta)} \right] \le 1 \qquad (24)$$

When *VSPI* is less than one(1), the system is stable. However, when its value is nearly closer to one (1), then system is unstable and near voltage collapse. where; V_r is the receiving-end voltage, δ is a phase angle, δ_r is the receiving-end voltage phase angle, δ_s is the sending-end voltage phase angle, a and b are the weighing coefficients.

Step 7: Check if there is any instability or collapse go to step 3, else go to step 7.
Step 8: The performance of the system were analyzed and the system collapse state were determined.

The flowchart for system stability assessment is shown in Figure 2.

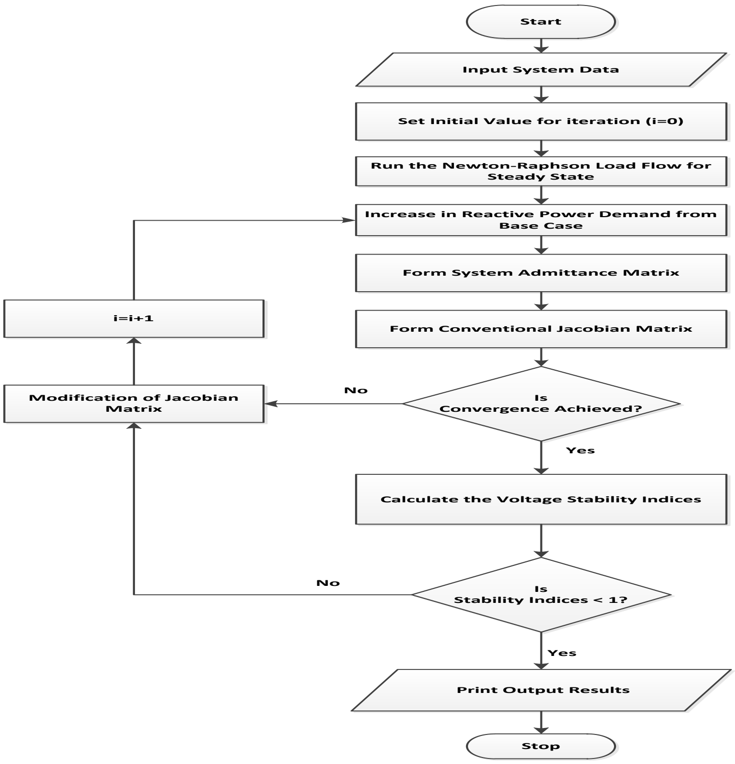

Figure 2: Flowchart of NR for System Stability Assessment

C. Implementation of Firefly Algorithm

In order to deliver optimum load stability that can maximize the load flow marginwhile satisfying bus voltage and other operating limits. Firefly Algorithm (FA) was employed as optimal load stability optimization technique to determine the proximity of voltage collapse point in power system. This technique optimally locates possible points of placement of compensation devices to mitigate against voltage collapse in the power system.

The following are the stepwise procedures for the implementation of the FA:

Step1: The system data'swere inputted while satisfying equality and inequality constraints;
Step 2: The FA parameters and constants were initialized;
Step 3: The 'n' number of fireflies were generated and iteration count were set to 1.
Step 4: The NRload flow were performed for base case and contingency;
Step 5: The fitness values of each firefly were evaluated using Equation (25).

$$ff = Max(VSI_{\min}) \qquad (25)$$

Step 6: The best values for all the fireflies from the fitness values were obtained and the best value among all the best values were identified.
Step 7: The distance of attraction of each firefly were determined using Equation (12)
Step 8: New values were calculated for all the fireflies and the line with the greatest VSPI was termed as the most critical line of the bus.
Step 9: The position of firefly were updated using Equation (26)

$$P_{i,k+1} = P_{i,k} + V_{i(new)} \qquad (26)$$

Step 10: New fitness values for the new positions were calculated;
Step 11: If the new fitness value for thefirefly is better than previous best value then best value for that firefly is set to present fitness value.
Step 12: The iteration count was increased and convenience were checked;
Step 13:The fireflies were ranked according to G_{best} (maximum load-ability).The brightest firefly position gavepossible optimal location of compensation device for voltage stability enhancement.

The flowchart for Firefly Algorithm is shown in Figure 3.

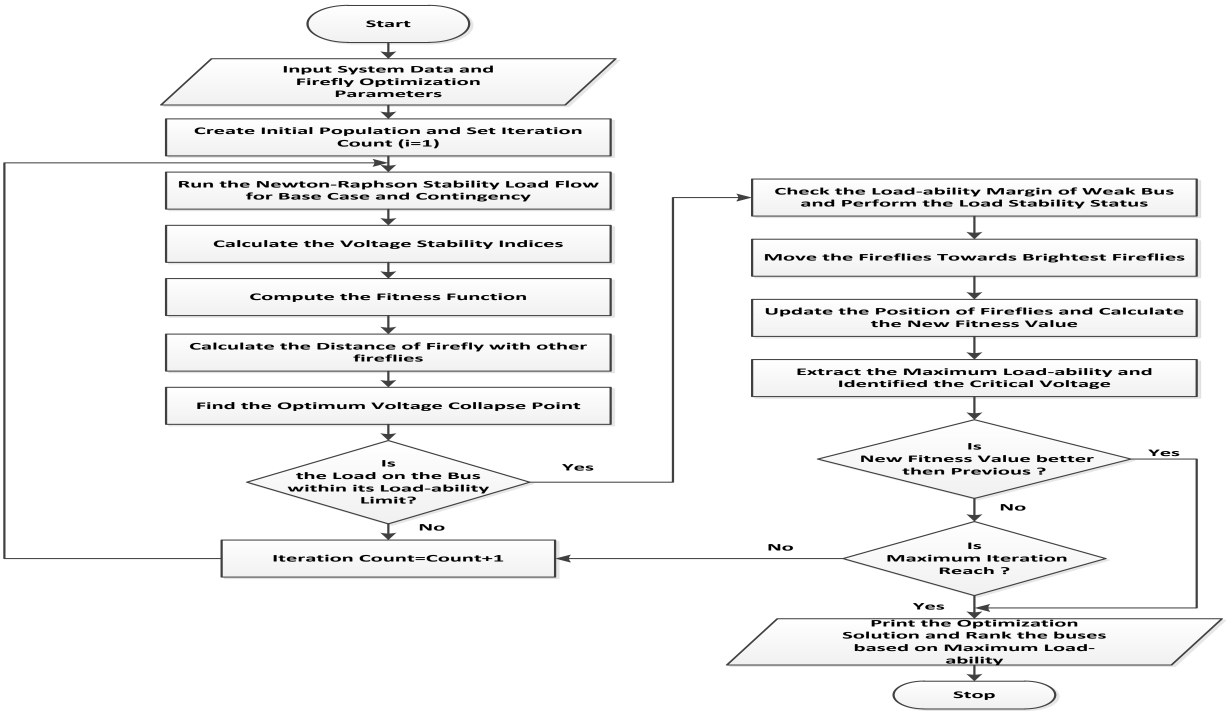

Figure 3: Flowchart of Firefly Algorithm

IV. RESULTS AND DISCUSSION

The simulation results of FAwith VSPI for assessment and prediction of voltage collapse on Nigerian power systemwere analyzed and presented. Power flow analysis was performed with permissible working rangevalues of 0.95 to 1.05 p.u. and the stability level of the system was determined. FA was employed to rectify the problem of voltage violations in the system, regulate reactive power flow limit and optimally locate possible points of placement of compensation devices in the system.

Figure 4 showed the comparison of voltage magnitudes with the bus number of the system for steady state. Buses 6, 13 and 17 with voltage magnitudes of 1.0580, 0.9360and 1.0510 p.u., respectively, were buses whose voltage falls short of the ±5 % tolerance margin of the voltage criterion. These buses are the potential buses for location ofcompensation devices.

In addition, Figure 5 displayed the VSPI results of the system for steady state and it was observed that the system was stable as none of VSPI result of each line closeto one (1).

Figure 6 depicted the comparison of voltage magnitude with the bus number of the system for contingency. It was observed that all the load buses had their voltage fell short of the ±5 % tolerance margin of the voltage criterion.

Furthermore, Figure 7 presented the VSPI results of the system for contingency. It was observed that the system was not stable as VSPI results of each line were greater than 1.

Figure 8 illustrated the comparison of voltage magnitude with the bus number of the system with FA. It was observed that the bus voltage limits that are violated under the contingency was rectified by having voltage magnitude at all the buses within voltage limit of ±5% .

Figure 9 presented the VSPI results of thesystem with application of FA. It was observed that the system was stable as many of VSPI results in each line were less than one (1) expect buses 6 and 16. These buses were the potential buses for best location of compensation devices for avertingagainst voltage collapse in the system. In addition, it was also observed that as the reactive power in these buses was increased, the values of voltage magnitude dropped while the VSPI values also increased till voltage collapse occur,

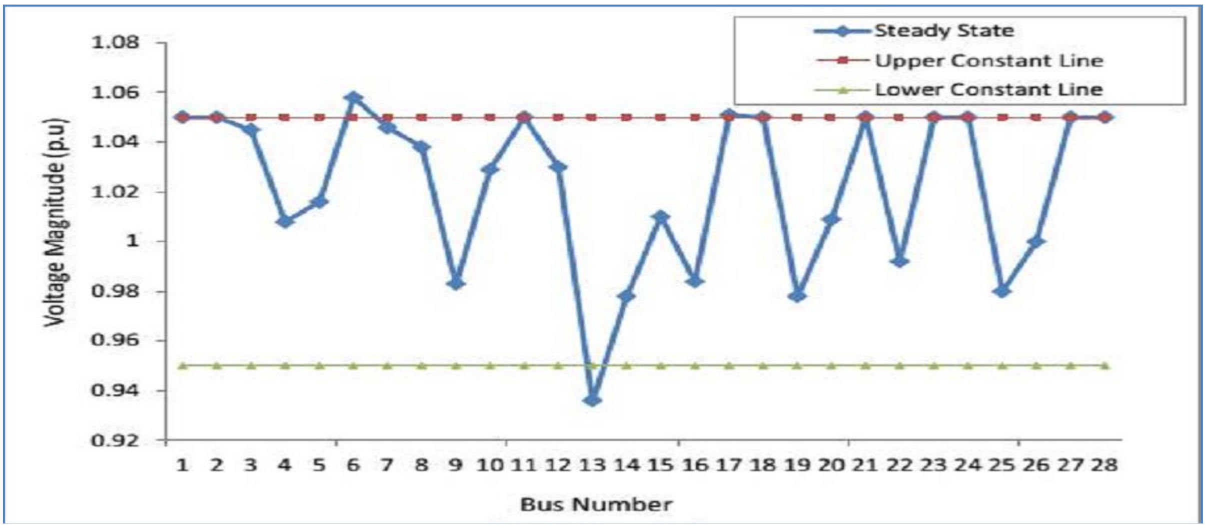

Figure 4: Comparison of Voltage Magnitude for Steady State

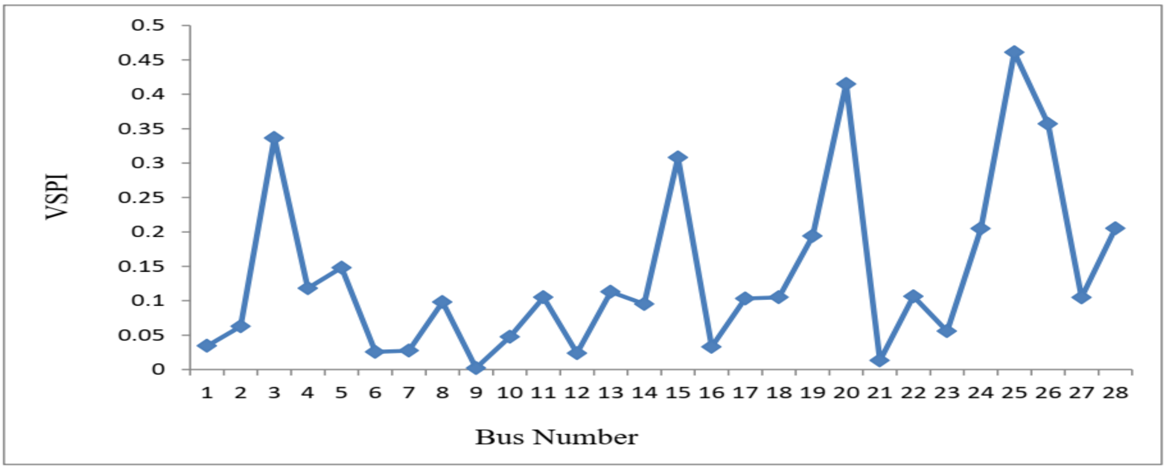

Figure 5: VSPI Result for Steady State

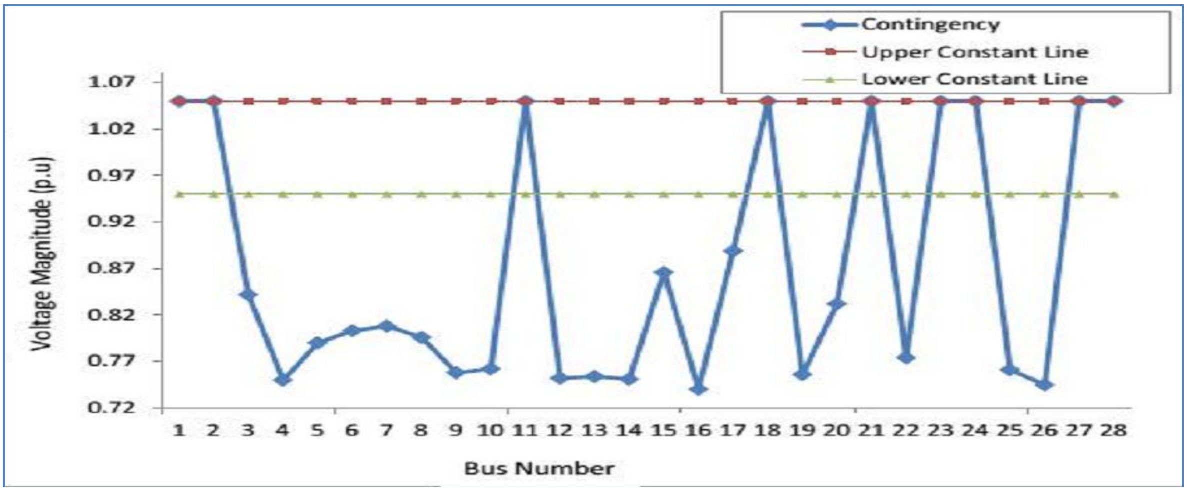

Figure 6: Comparison of Voltage Magnitude for Contingency

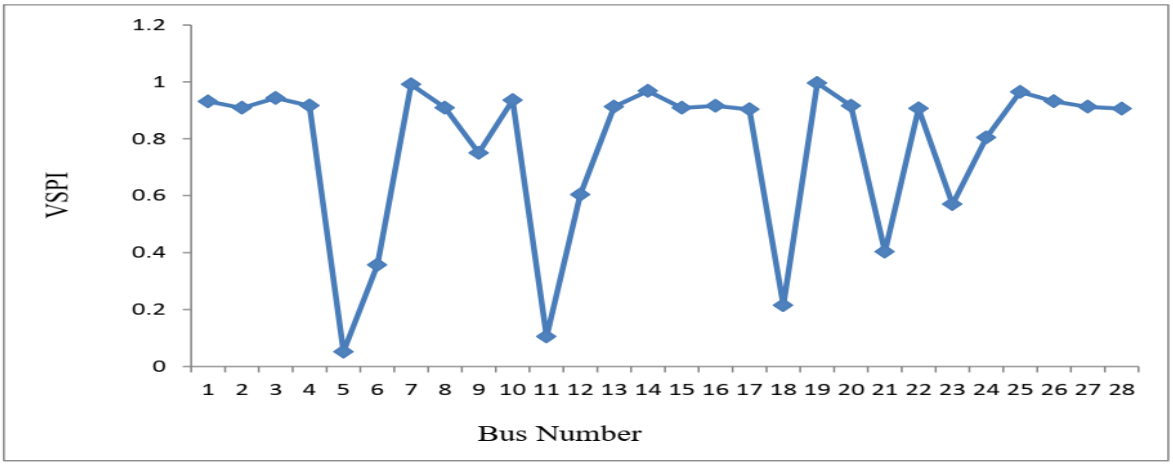

Figure 7: VSPI Result for Contingency

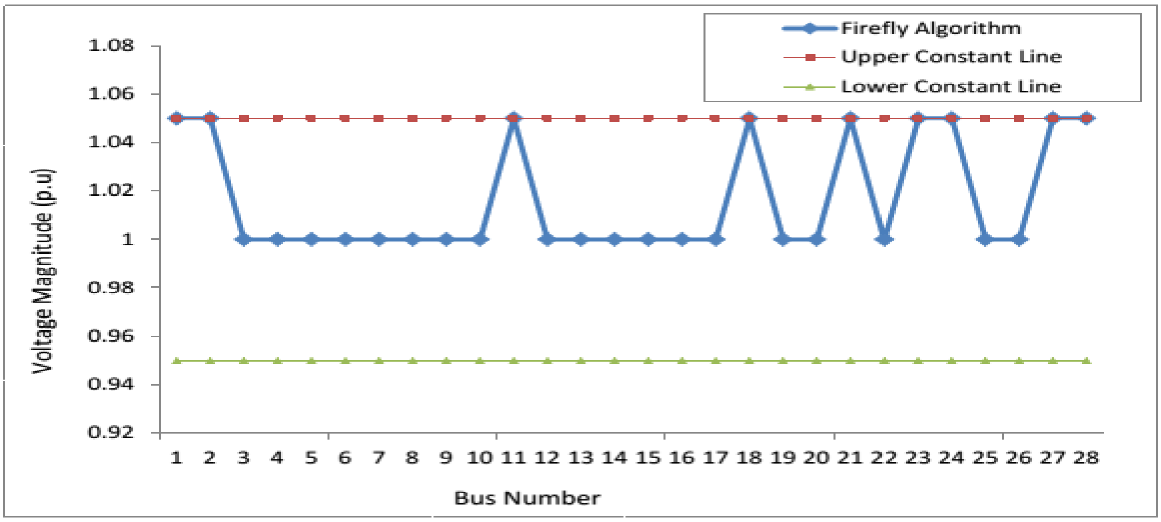

Figure 8: Comparison Voltage Magnitude with FA

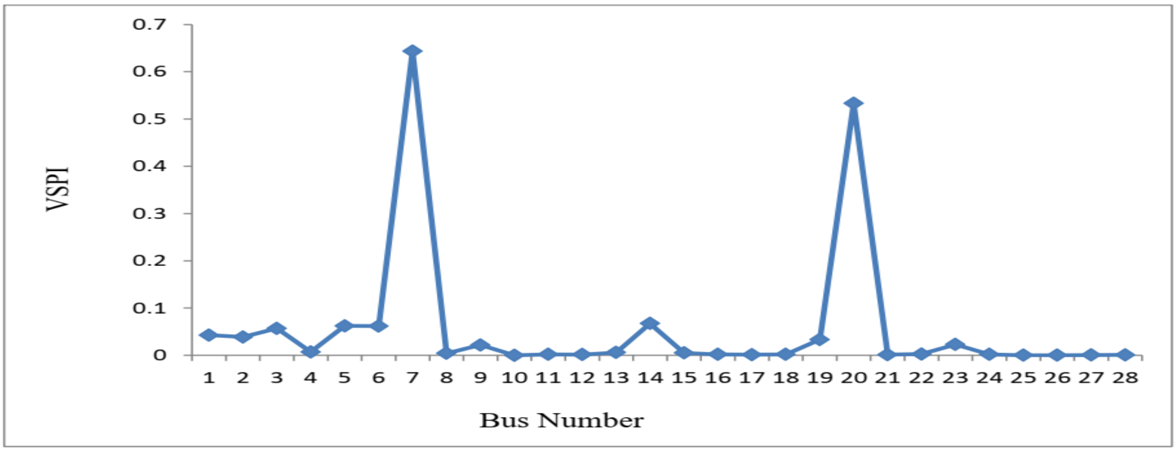

Figure 9: VSPI Result with FA

V. CONCLUSION

In this study, FA with VSPI for assessment and prediction of voltage collapse on Nigerian power system has successfully presented. NR load flow was performed for both steady state and contingency for calculation of VSPI. The FA was employed as optimal load stability technique to rectify the problem of voltage violations, regulate the reactive load capacity and optimally locate possible pointsof placement of compensation devices in the system. The analysis revealed that with application of FA, the bus voltage limits violation was rectified to voltage limit of ±5% tolerance, the reactive load capacity of each bus was regulated to base value and the potential bus for best location of compensation devices for averting against voltage collapse were identified. The simulation results obtained verify the efficiency of the FA with VSPI for assessment and prediction of voltage collapse point.

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