Development Of a Line-Voltage Stability Index with Modified Equilibrum Optimizer for Identification of Critical Buses in Electrical Power System

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Abstract

Inappropriate identification of critical buses for placement of power electronic devices which improve the post disturbance recovery voltages in power system, results in voltage instability which brings great challenges to monitoring of power transmission and expansion planning. This paper developed a Line-Voltage Stability Index (L-VSI) with Equilibrium Optimizer (EO) to identify the critical buses and to obtain the global optimal solutions for optimum location of the power electronic devices in electrical power system. The optimal L-VSI with EO algorithm was developed using the weighted sum of normalized value of the system line loss and generator bus voltage based on the oscillation damping ratio. Simulation was done in MATLAB R2023a. The approach was evaluated with data sets of Nigerian 31- bus systems. The effectiveness of the approach in terms of generator damping ratio and total active power loss was compared with other stability indices. The results showed that the optimal L-VSI provided better results when compared with the results obtained from other stability indices during contingency. Thus, this study would help the Independent System Operators (ISO) to identify weak buses with high impact of voltage instability in electrical power system.

Keywords: *Critical Buses, Power Electronics, Line-Voltage Stability Index, Equilibrium Optimizer, Independent System Operator,*

1. INTRODUCTION

In a deregulated power system, the electric power demand is increasing everyday due to the increasing number of consumers with the addition of sensitive power-electronic equipment which may lead to overloads, loss of generation and constant power failure [1, 2]. This high demand of electricity has made the power management to operate power system closer to their limits which has affected the power system expansion plans and subject to transient instability, which also resulted in limited supply of reactive power from synchronous generators during disturbance [3]. One of the most common technical solutions in dealing with the high demand of electricity and to improve the transient stability is the construction of new transmission lines, but the process is both time-consuming and costly, and may cause short and long-term disruptions to the environment [4-9].

However, breaking innovations in power electronic devices such as Voltage Source Converter (VSC) based Flexible Alternating Current Transmission System (FACTS) devices are alternatives to long-distance alternating current transmission line and has provided better solution in driving the transition of power systems towards a carbon-free paradigm while maintaining the current standards of quality, efficiency and resilience [2, 10]. In addition, incorporation of power generators such as Thermo-Electric Generators (TEGs) and wind generation bring great innovation to transmission expansion planning and proper control strategies to identify critical buses in the power system. Optimal placement of the equipment is very much useful for power system monitoring and expansion to prevent possible voltage instability and to meet the increasing loads, as improper controller strategies will lead to non-optimal placement of the VSC which could increase the system instability and thwarting the power system expansion planning [3, 9, 11 -15]

Several voltage stability assessments and indicators such as Control Lyapunov Function (CLF), Eigenvalue analysis, voltage instability proximity indicator, Voltage Stability Index (VSI) and Fast Voltage Stability Index (FVSI) among others have been presented to quantify proximity to voltage instability in power system [4, 12]. However, some of these methods are computationally demanding which makes them unsuitable for on-line applications, exhibit nonlinear behavior due to discontinuities caused by system controls and others were reported not to perform as expected under ill conditions. Thus, it is quite evident that there is still the need for a simple reliable voltage stability assessment tool [1, 7, 15-22].

Therefore, the study improved the stability of present Nigerian transmission system by developing an optimal Line-Voltage Stability Index (L-VSI) to identify critical buses for effective placement of VSC in the power system. This help to identify weak buses with high impact of voltage instability and the most critical line connected to it.

I. PROBLEM FORMULATION

Efforts have been made towards analyzing and solving the problem of identification of critical buses for optimal placement of generator and power electronics in electrical power system during contingency. Different stability indices have been employed to predict and identify the correct placement for compensator devices as to find solution to system instability and system collapse. Each technique has tried to solve the problem with various objectives and constraints. However, most of the indexes showed a non-linear behavior near the collapse point and in the presence of system control limits such as generator oscillation damping ratio limits. Thus, the main objective is to optimize the generator load bus with the lowest value of damping oscillation ratio that would enhance the voltage stability of the power system within acceptable voltage limit and minimize the system power loss. The objective is formulated as Equation (1) [23-27]:

$$OF = Optimize \sum_{\substack{i=1 \\ j\neq 1}}^{N} \left(|V_i|^2 Y_{Li} \cos\theta_{Li} + j\frac{\delta}{\partial t} K_D + \Delta P_{GLi} \right) \quad (1)$$

Subjected to stability constraint: damping ratio limit as in Equation (2):

$$0.03 \le K_D \le 0.05 \tag{2}$$

where; P_{GLi} is the equivalent generator power obtained at each load bus, V_i is the generator terminal voltage, Y_{Li} is the system admittance matrix at load bus I, ∂t is the damping input signal transmission delay, K_D is the generator damping ratio coefficient, δ is the rotor angle, θ is the phase angle,

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II. DEVELOPMENT OF OPTIMAL LINE-VOLTAGE STABILITY INDEX

Line-Voltage Stability Index (L-VSI) from line loss and generator bus voltage based on the damping ratio at each load bus was developed using modified Equilibrium Optimizer (EO).

The developed index was utilized based on the following assumption:

i. The power system is a balanced 3-phase system
ii. The generators were classified as constant load bus (PQ) or generator bus (PV) nodes.
iii. The minimum and maximum operating values of damping ratio of the generator at any bus were in the range of 0.03 and 0.05.

A. *Line-voltage stability index model*

The Line-Voltage Stability Index (L-VSI) was developed by considering a synchronous machine connected to infinite bus in Figure 1, the generator voltage at steady state is given as Equations (3)

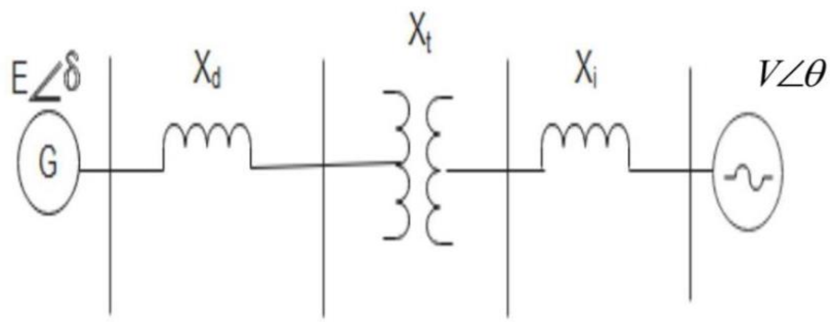

Figure 1: Single Machine/Infinite Bus System

$$E = V + jX_S\left[\frac{P_g - jQ_g}{V_i^*}\right] \tag{3}$$

The behavior of the generator at steady state equilibrium point is given as in Equation (4):

$$\frac{H\partial^2\delta}{\omega\partial t^2} = P_m - P_e \tag{4}$$

The power system generator oscillation damping ratio for transient stability of the transmission system was computed by adjusting the generator load power from 50 to 90 % (acceptable minimum and maximum range of power generator). With disturbance (contingency), the behavior of generator was determined using Equation (5) [28 -32]:

$$\frac{H\partial^2\Delta\delta}{\omega\cdot\partial t^2} = \Delta P_m - \Delta P_e \tag{5}$$

The change in the generator damping ratio was calculated using Equation (6) [33, 34]:

$$\Delta K_{GDi} = \int_{0.03}^{0.05}\left(\Delta P_{GL} - \left|\Delta P_{ei} + \frac{H\partial^2\Delta\delta}{\omega\partial t^2}\right|\right)\partial t \tag{6}$$

Then, the system line loss and change in bus voltage based on the damping ratio were calculated using Equations (7) and (8), respectively;

$$L_{Lossi} = \sum_{i=1}^{N}\left(\frac{X_s}{V_i^2}P_{Li} + jQ_{Li}\right) + \Delta K_{Di} \tag{7}$$

$$\Delta V_{Gi} = \sum_{i=1}^{N} Y_{Gij}\left(\frac{X_S}{V_i^2}\right) + \Delta K_{Di} \tag{8}$$

The L-VSI was developed using the weighted sum of normalized value of the system line loss and generator bus voltage based on the damping ratio in Equations (7) and (8), respectively. This computed Equation was termed L-VSI as given in Equations (9):

$$L-VSI = \sum_{i=1}^{N}\left[w_1\sum\left(\frac{Y_G X_S}{V_i^2}\right) + w_2\sum\left(\frac{P_{Li}X_S}{V_i^2} + jQ_{Li}\right) + \Delta K_{Di}\right] \tag{9}$$

where; $P_{L\,i}\, and\, Q_{Li}$ are active and reactive power loss, X_S is the system reactance, V_i is the system internal voltage, Y_G is the element of generator bus admittance matrix, w_1 is the weighted coefficient for line loss which was considered to be 0.9, w_2 is the weighted coefficient for generator bus voltage which was considered to be 0.1, K_D is the generator damping ration coefficient, N is the number of bus.

B. Application of Modified Equilibrium Optimizer

Two main improvements for EO were made. The first improvement involved employing the EO algorithm at the initialization phase. This improvement enhanced the diversity of the population (number of buses). The second improvement involved enhancing the EO exploration parameters based on fitness function with L-VSI in Equation (9). This improvement strengthens the EO search abilities in both local and global search.

In the first improvement, EO particles were evaluated using fitness function in Equation (10) and each particle was updated using Equations (11) to (12) [35-38]:

$$\downarrow fitness = \alpha\gamma(R) + \beta\frac{[F]}{[N]} \tag{10}$$

$$C_{eq.pool} = \{C_{eq(1)}, C_{eq(2)}, C_{eq(3)}, C_{eq(4)}, C_{eq(ave)}\} \tag{11}$$

$$\vec{F} = a_1 \sin\left(\vec{r} - 0.5\right)\cdot[e^{-\vec{\lambda}t} - 1] \tag{12}$$

$$\vec{G}_0 = \overrightarrow{GCP}\left(\vec{C}_{eq} - \vec{\lambda}\vec{C}\right) \tag{13}$$

In the second improvement, the EO exploration parameters based on fitness function with L-VSI was evaluated using Equation (14). The particles (load buses) were evaluated for their fitness function and each particle (bus) was updated with its concentration based on the fitness value;

$$ff = \min \ \alpha\gamma\left(P_{Gbus}\right) + \beta \frac{F_{L-VSI}}{N_{bus}} \tag{14}$$

where; $\gamma\left(P_{Gbuss}\right)$ is the objective function classifier error, F_{L-VSI} is the number of selected critical buses, and N_{bus} is the total number of features (buses). In addition, α, β are EO feature subsets which are in two factors where; $\alpha \in [0,1]$ and $\beta = (1-\alpha)$.

The EO search agents randomly updated its concentration with respect to best solutions (equilibrium candidates) to the final equilibrium state (optimal result). Then, the load bus with the highest value of L-VSI based on the fitness function was regarded as weak bus for potential placement of generator and VSC devices in power system,

The simulation was carried out in MATLAB R(2023a) according to the following steps:

Step 1: The system data such as line, generation, and load data were inputed;

Step 2: Based on swing equation, the stability of the power system under steady state condition were determined using Equation (4);

Step 3: Generator load power was varied between 50 and 90 % (20% interval) and the stability of the power system at contingency are determined using Equation (5);

Step 5: The change in generator damping ratio were calculated using Equation (6):

Step 6: The system line loss and change in bus voltage based on the damping ratio were calculated using Equations (7) and (8), respectively;

Step 7: Determine the L-VSI using the weighted sum of normalized value of the system line loss and generator bus voltage in Step 6 as in Equations (9):

Step 8: The EO population were initialized and iterations count were set;

Step 9: EO fitness value of each search agent were evaluated using Equation (10);

Step 10: For each search agent, the values of equilibrium candidates and pool, exponential term and generation rate were evaluated using Equations (11) to (13), respectively:

Step 11: The EO exploration phase based on fitness function were modified and position of the EO current search agent based on L-VSI were updated using Equation (14);

Step 12: The new equilibrium state for each particle (optimal result) were updated based on the current search agent in Step 11, otherwise step 5 is repeated;

Step 13: Stop

III. IMPLEMENTATIONS OF THE APPROACH

The effectiveness of optimal L-VSI with EO to identify the critical buses for optimal location of the power electronics devices in the power system was implemented on Nigerian 31-bus transmission system shown in Figure 2. This was carried out due to the epileptic nature of the Nigerian power system which makes it more often to experience voltage instability. The power system has a span length of about 5,680 km with 7 effective generation plants, 24 load stations and 60 transmission lines delivering power at its rated voltage level and number of transmission substation. The data set of Nigerian 31-bus transmission system was sourced from National Control Centre (NCC) of the Transmission Company of Nigeria (TCN), Osogbo, Osun State, Nigeria [12, 14, 39 -40].

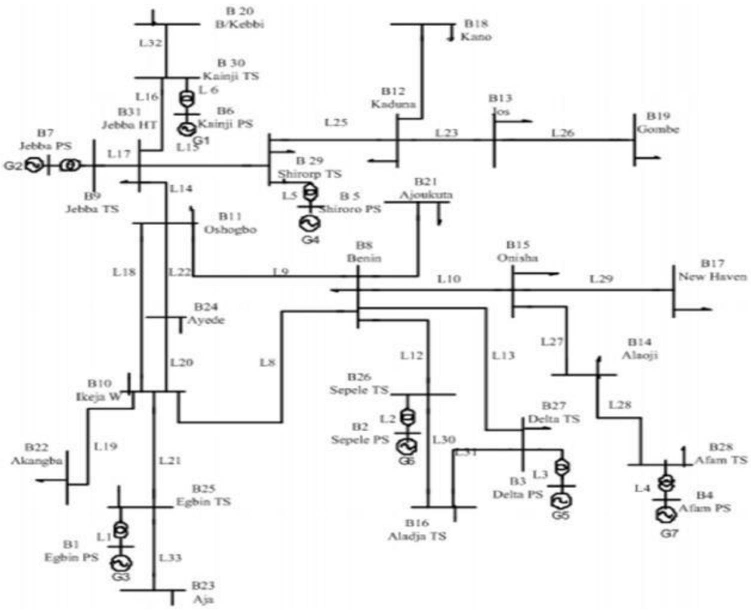

Figure 2: Nigerian 330 kV, 31 –Bus Transmission System

IV. COMPARISION WITH OTHER VOLTAGE STABILITY INDICES

The L-VSI was used to find the most critical bus for allocating the power electronics in the Nigerian 31-bus transmission system. Simulation was done in MATLAB R(2023a) and result optimization solution based on objective functions in Equation (1) were compared with Line Stability Index (LSI), Fast Voltage Stability Index (FVSI), Line Stability Factor (LSF), Voltage Collapse Point Indicator (VCPI) and Voltage Stability Prediction Index (VSPI), respectively.

The simulation was done according to the following steps:

Step 1: The system data such as line, generation and load data were inputed;

Step 2: The initial values of the bus voltage limits in the initial population were generated;

Step 3: Based on swing equation, the stability of the power system under steady state and contingency condition were determined;

Step 4: The L-VSI at each bus were calculated. All the bus locations except the slack bus are tried for optimal location for the compensator devices using Equations (9):

Step 5: The EO fitness value of each search agent based on L-VSI are evaluated using Equation (14);

Step 6: The LSI, FVSI, LSF, VCPI and VSPI at each are evaluated using Equations (15), (16), (17), (18) and (19), respectively [22, 28, 39, 40],

$$LSI = \frac{4XQ_r}{|V_s|^2 Sin^2(\theta - \delta)} \leq 1 \tag{15}$$

$$FVSI = \frac{4Z^2 Q_r}{V_s^2 X} \leq 1 \quad (16)$$

$$LSF = 4\left(\frac{X}{V_s^2}\right)\left(\frac{X}{V_s^2} P_s + Q_r\right) \quad (17)$$

$$VCPI = \left| 1 - \frac{1}{V_r} \sum_{\substack{i=1 \\ i \neq r}}^{n} V_i \right| \quad (18)$$

$$VSPI = \frac{4Q_r}{|V_s|^2}\left[a\frac{Z^2}{X} - (a-1)\frac{1}{Sin^2(\theta - \delta)} \right] \leq 1 \quad (19)$$

Step 7: The new equilibrium state for each particle (optimal result) are updated based on the stability indices.

Step 8: The generator excitation voltage were updated using Equation (3.45),

Step 9: The electrical power output of each generator with damping were determined using Equation (20) [34, 39];

$$P_{ei} = E_i^2 Y_{ii} \cos\theta_{ii} + \sum_{\substack{i=1 \\ j \neq 1}}^{N} |E_i||E_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) + D_{HVDC} \quad (20)$$

Step 10: The size of the controllers required for compensation were determined. using Equation (21) [32, 40];

$$S_{Value} = \frac{Q_{HVDC}}{2\pi \cdot f \cdot V_i^2} \quad (21)$$

Step 11: The cost of the controllers are determined based on the size in Step 10;

Step 12: Compare system stability based on each stability indices.

Step 12: Stop.

V. RESULTS AND DISCUSSION

The simulation results of the developed L-VSI optimized with EO algorithm at contingency on Nigerian 31-bus power system are presented. This optimized L-VSI was used as stability control strategies to identify the critical buses and obtain the global optimal solutions for optimum location of the compensator devices in the two power system. The load bus with the highest value of L-VSI based on Equation (14) was regarded as weak bus for potential placement of power electronics devices in the power system.

Figure 3 illustrated the relationship between the optimized L-VSI and bus number of Nigerian 31-bus at 50% loading. It could be observed that buses 5, 11 and 21 were selected buses for optimal location of power electronics devices in the power system. These selected optimal buses have L-VSI value of 0.99, 0.88 and 0.87, respectively. In addition, Table 1 presented the load flow result of the selected buses at 50% loading. It was observed that the selected optimal buses had voltage magnitudes of 0.9554, 0.9500 and 0.9561 p.u with active line power of 1.25, 0.85 and 0.08 MW. The total active and reactive power losses in the system are 397.94 MW and 284.76MVar respectively.

Figure 4 presented the relationship between L-VSI and number of bus of the power system at 70% loading. Buses 5, 11 and 21 were selected buses for optimal placement of compensator devices in the power system with L-VSI values of 0.96, 0.98 and 0.97, respectively. In addition, Table 2 displayed the load flow results of the selected buses. It was observed that the total active and reactive power losses in the system at 70% loading were 482.12 MW and 325.36 MVar.

Figure 5 presented the relationship between optimized L-VSI and bus number of Nigerian 31-bus power system at 90% loading. In addition, buses 5, 11 and 21 with L-VSI value of 0.99, 0.97 and 0.99, respectively, were selected as the best locations for placement of compensator devices in the power system. Table 3 presented the load flow results of the selected optimal buses. It could be observed that the selected buses have a voltage magnitude of 0.9503, 0.9506 and 0.9503 p.u. with active line power of 0.98, 0.66 and 0.04 MW. In addition, the total active and reactive power losses in the system at 90% loading are 495.95 MW and 381.53 MVar respectively.

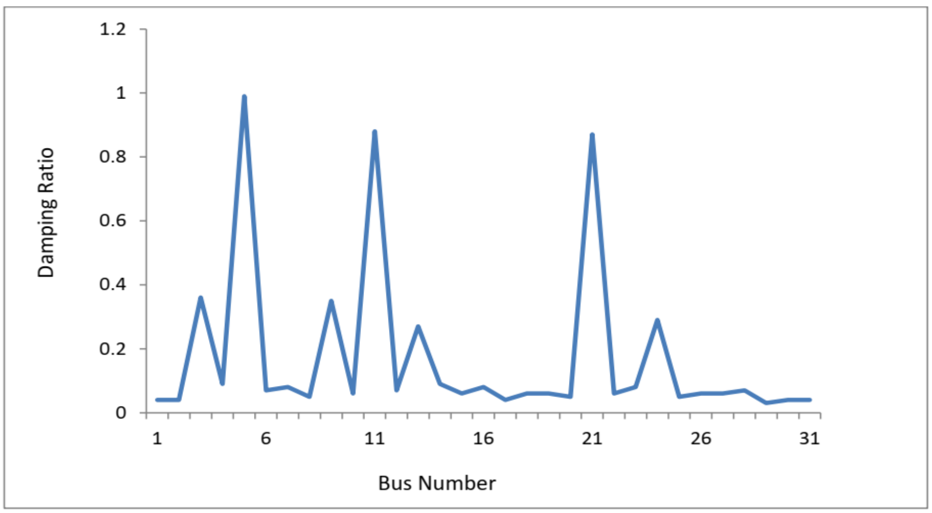

Figure 3: Optimized L-VSI and bus number of Nigerian 31-bus system at 50% loading

Table 1: Load flow results of selected buses of Nigerian 31-bus at 50% loading

Bus No	Voltage Magnitude (p.u)	Load (MW)	Load (MVar)	Line Loss (MW)	Line Loss (MVAr)
5	0.9554	1.25	0.67	7.76	10.06
11	0.9500	0.85	0.90	43.98	-32.30
21	0.9561	0.02	0.40	0.33	1.88

Total				397.84	284.76

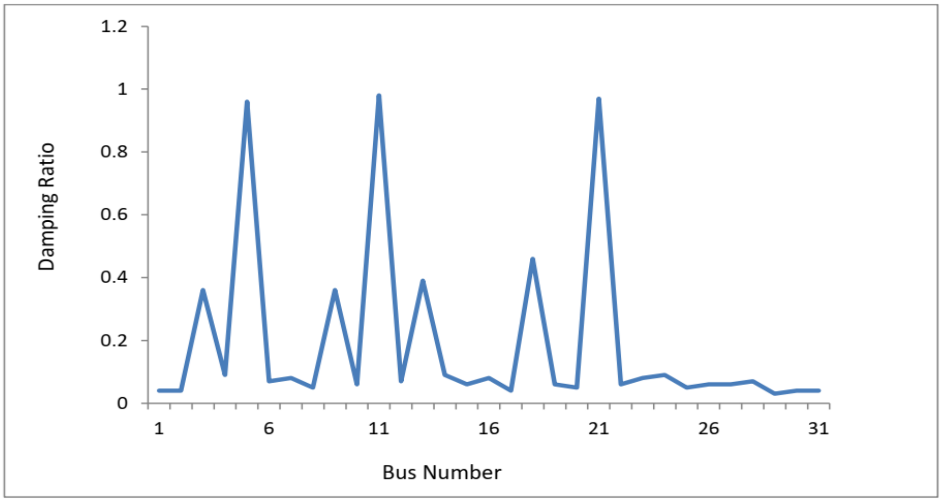

Figure 4: Optimized L-VSI and bus number of Nigerian 31-bus system at 70% loading

Table 2: Load flow results of selected buses of Nigerian 31-bus at 70% loading

Bus No	Voltage Magnitude (p.u)	Load (MW)	Load (MVar)	Line Loss (MW)	Line Loss (MVAr)
5	0.9500	2.0	2.0	9.15	10.03
11	0.9500	2.03	0.99	51.03	-37.59
21	0.9500	0.02	0.41	-0.97	-0.54
Total				482.12	325.86

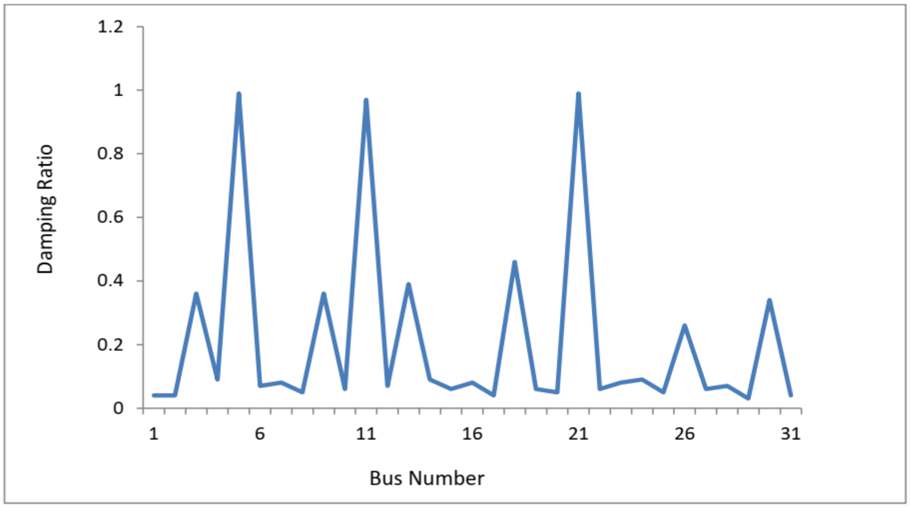

Figure 5: Optimized L-VSI and bus number of Nigerian 31-bus system at 90% loading

Table 3: Load flow results of selected buses of Nigerian 31-bus at 90% loading

Bus No	Voltage Magnitude (p.u)	Load (MW)	Load (MVar)	Line Loss (MW)	Line Loss (MVAr)
5	0.9503	0.98	0.66	9.26	12.95
11	0.9506	0.66	0.88	49.43	-41.64
21	0.9503	0.04	0.36	1.63	-0.70
TOTAL				495.95	381.53

In addition, Figure 6 illustrated the comparisons of damping ratio with bus number of Nigerian 31-bus at 90% loading. The buses for optimal placements for compensation devices in the power system with application of optimal L-VSI were buses 5, 11 and 21. It was observed that these buses were the buses whose generator oscillation damping ratio fell short of the working range with damping ratio of 0.01 each. However, with applications of LSI, FVSI, LSF, VCPI and VSPI, all the load buses in the power system were selected to be most critical buses for allocation of the power electronics devices in the power system. The damping ratio of all the load buses were falls short of the working range value.

Figure 7 showed the comparisons of voltage magnitude with bus number of Nigerian 31-bus at 90% loading. With application of optimal L-VSI, the voltage magnitude of the selected buses 5, 11 and 21 were 0.9503, o.9605 and 0.9503 p.u. respectively. Also, with applications of LSI, FVSI, LSF, VCPI and VSPI, the voltage magnitude of all the load buses in the power system were reduced compared to application of L-VSI. Furthermore, Figure 8 presented the comparison of total active power loses of the Nigerian 31-bus system at 90% loading. The total active power losses in the power system for contingency, with optimal L-VSI, LSI, FVSI, LSF, VCPI and VSPI were 684.52, 500.96, 520.96, 527.10, 529.31, 530.32 and 530.30 MW, respectively.

It was also observed that the results obtained based on voltage magnitude with optimal L-VSI were varied when compared with other voltage stability indices, respectively. However, the results obtained from optimal L-VSI are in line with the voltage tolerance margin of the voltage criterion of ±5 %. The results obtained with applications of LSI, FVSI, LSF, VCPI and VSPI showed that the voltage magnitudes of all the load buses in the power system were out of voltage tolerance margin. Furthermore, the results of total active power loss in the power system obtained with optimal L-VSI gave better results and compared favorably well with the results obtained from LSI, FVSI, LSF, VCPI and VSPI. Thus, it can be verified that the application of optimal L-VSI is suitable for selected best placement for power electronics devices in electrical power system.

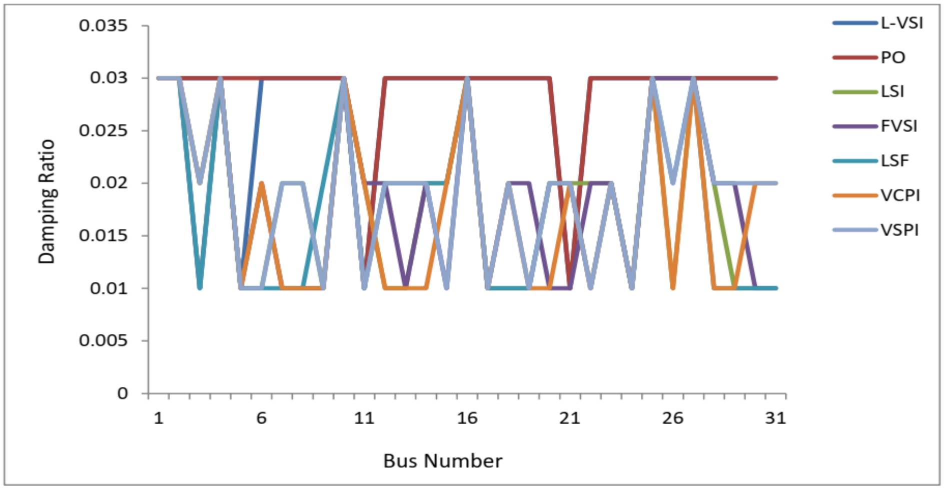

Figure 6: Comparison of damping ratio of Nigerian 31-bus system at contingency with different approaches

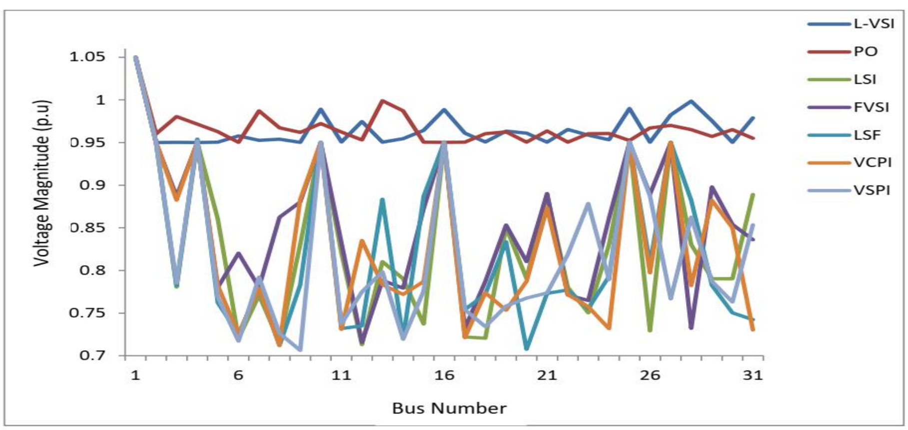

Figure 7: Comparison of voltage magnitude of Nigerian 31-bus system at contingency with different approaches

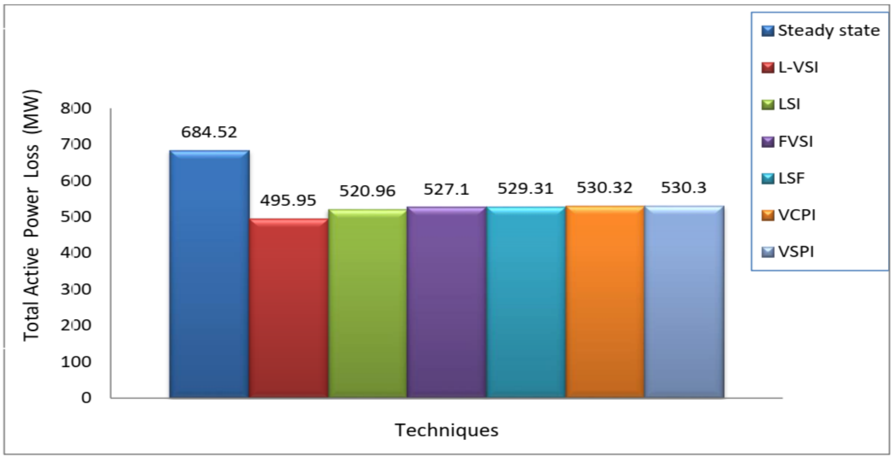

Figure 8: Comparison of active power loss of Nigerian 31-bus system at contingency with different approaches

VI. CONCLUSION

This study has successfully developed and presented the Line Voltage Stability Index (L-VSI) optimized with modified Equilibrium Optimizer (EO) for effective identification of critical buses in power system during disturbance. The L-VSI was developed from formulated mathematical model of line loss and bus voltage based on generator oscillation damping ratio using swing equation method. The developed optimized L-VSI was implemented on Nigerian 31-bus transmission system. The performance of the optimized L-VSI based on damping ratio, bus voltage and power loss were compared with other voltage stability indices. The results verified the accuracy and efficiency of the optimal L-VSI for effective identification of critical buses in electric power system. Therefore, it can be concluded that, the approach developed in this study is credible, efficient and suitable for identification of critical buses for optimal placement of compensator devices in electric power system at contingency

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