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An Alternative Approach to Voltage Collapse Prediction in a Practical Nigerian 330-kV Interconnected Power Grid

Akintunde S. ALAYANDE[1], Claudius O.A. AWOSOPE[2], Ignatius K. OKAKWU[3], Olanike O. ADE-IKUESAN[4], John M. ALAYANDE[5]

[1] *Department of Electrical and Electronics Engineering, University of Lagos, Nigeria*
[2] *Department of Electrical and Information Engineering, Covenant University, Ota, Nigeria*
[3] *Department of Electrical and Electronics Engineering, University of Benin, Nigeria*
[4] *Department of Electrical and Electronics Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria*
[5] *Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, Nigeria*

aalayande@unilag.edu.ng,coaawosoper@yahoo.co.uk,igokakwu@yahoo.com,ayanmayowa2012@yahoo.com

Corresponding Author: igokakwu@yahoo.com

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Abstract: *The rapid increase in electrical power demand without a corresponding compensation from generation has resulted in various total blackouts within power systems. Consequently, various cascading failures have been witnessed within modern power networks in recent times. This paper, therefore, proposes a new method for predicting the points of voltage collapse eruption within any given practical power network. The mathematical formulations of the proposed approach-based circuit theory are presented. A new stability index, termed Load Bus Proximity Index (LBPI), which is able to predict the points of voltage collapse within the network, is then formulated. The effectiveness of the proposed approach is tested on the standard IEEE 5-bus network as well as the practical Nigerian 28-bus network. The results show that the proposed alternative approach could be useful in predicting the point of voltage insecurity within practical power networks. This information could be useful to power system operators in minimizing* ***the occurrence*** *voltage collapse within practical power networks.*

Keywords: *compensation, cascading failures, load bus proximity index, stability index, voltage collapse.*

1. INTRODUCTION

The **quest to satisfy** continuous increase in the demand for electrical power has made power network increasingly complex and difficult to maintain in a stable operating mode, leading to security problem. Voltage security problem often forces networks to be operated at a point harmfully near voltage security limits whenever it happens in a network. This sometimes results in system collapse or blackout. Some well-known blackouts directly associated with voltage collapse, which cost millions of dollars are documented in [1]. Other blackouts reported occurred in Italy and Sweden-East Denmark [2], USA and Canada [3], London, UK [4], Croatia and Bosnia Herzegovina [5]. All these occurred in 2003 and others that are reported include that of Greece in 2004 [6-7], Russia in 2005 and Germany in 2006 [2, 8-9].

Instability in power networks has proved to be a major concern to system engineers, operators and even researchers. This is as a result of its overall effect on power system operation and planning. High reactive power demand as well as high reactive power loss in transmission network often results in voltage collapse problem [10]. Voltage collapse has the tendency to occur once a system is operated close to its security limits. It should be noted that network voltage stability at all points plays an important role in preventing network collapse. Therefore, for a power system to be reliably operated, it is necessary to maintain a considerable security limit in both the normal operating condition and under contingency cases. Hence, voltage collapse prediction is an important issue in modern power systems operations.

Several methods have been used to measure voltage stability by estimating voltage collapse point. The use of various indices has been proposed for identification of the distance to the voltage insecurity within a power network. For instance, a matrix-based VaR model for risk identification in power networks has been developed in [11]. Jacobian matrix singularity for monitoring the smallest eigenvalue is employed in [12-13], eigenvalues and eigenvectors computations using reduced Jacobian matrix named as modal analysis are employed in [14,15] and voltage collapse prediction index (*VCPI*) to evaluate voltage stability and predict voltage collapse has been introduced in [16] while an improved voltage stability index designated as L_{ij} (taking the influence of load model into account) has been described in [17]. The use of different voltage security indices as a conventional means of voltage security margin analysis has been extensively applied and documented in [18]. This paper, therefore, contributes to the active stream of knowledge by presenting an alternative stability index, LBPI. This new index serves as a new approach for predicting voltage stability limits in practical networks, where system transmission lines and loads are both analysed based on load admittance and voltages. The developed index can accurately identify the weak buses within the network as well as predicting the point of collapse for the system as a whole. This makes it a powerful tool in measuring voltage stability. The proposed index could also be used to prevent future blackout incidents. The applicability of the developed model is demonstrated on both the standard IEEE 5-bus network and the practical Nigerian 28-bus network to show its effectiveness and efficiency.

The remaining sections of the paper are organized as follows: Section 2 of the paper presents the mathematical formulations. Section 3 presents numerical examples. Results and discussion are presented in section 4 while conclusion is presented in section 5.

2. PROPOSED STABILITY INDEX FORMULATION

Consider a simple 2-bus power network consisting of a generator bus and a load bus shown in Figure 1.

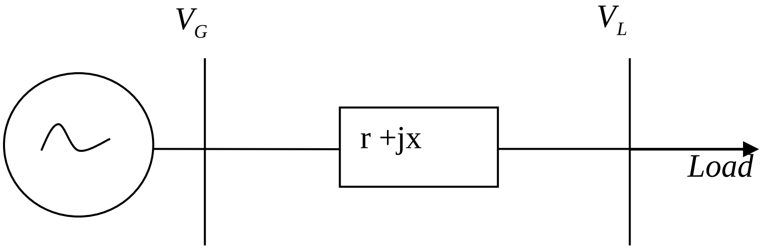

Figure 1: A Simple 2-bus power system network

From Figure 1, Ohm’s law can be expressed as

$$[I_L]_{n\times 1} = [Y_{LL}]_{n\times n}\,[V_L]_{n\times 1} \tag{1}$$

where $[I_L]$ = Load current vector, Y_{LL} represents the load-load admittance when the influence of generators have been eliminated and $[V_L]$ = Load bus voltage vector

The load complex power is given as

$$S_L = V_L\, I_L^{\,*} \tag{2}$$

Substitution of equation (1) into equation (2) gives

$$S_L = V_L\, Y_{LL}^{\,*}\, V_L^* \tag{3}$$

Alternatively,

$$S_L = Y_{LL}^{\,*}\, V_L^2 \tag{4}$$

Combining equations (3) and (4) results in

$$\left|\frac{S_L}{Y_{LL}^{\,*}\, V_L^2}\right| = 1 \tag{5}$$

Therefore, the measure of stability for any given power network is given by the condition

$$\left|\frac{S_L}{Y_{LL}^{\,*}\, V_L^2}\right| \le 1 \tag{6}$$

where

$$V_L = |V_L|(\cos\delta_L + j\sin\delta_L)$$

$$Y_{LL} = G_{LL} + jB_{LL}$$

Hence equation (5) can be re-written as

$$\left| \frac{S_L}{|V_L|^2 [\cos\delta_L + j\sin\delta_L]^2 [G_{LL} + jB_{LL}]^*} \right| \leq 1 \qquad (7)$$

Therefore, with the following assumptions that $\delta_L \to 0^0$, $\cos\delta_L \approx 1$ and $\sin\delta_L \approx 0$, equation (7) becomes

$$\left| \frac{S_L}{|V_L|^2 [G_{LL} - jB_{LL}]} \right| \leq 1 \qquad (8)$$

Equation (8) is code named Load Bus Proximity Index (LBPI) and it is limited to values between zero and unity indicating system stability margins. Voltage stability of a network is compromised whenever the boundary condition is violated. As the value of LBPI approaches unity, the stability margin is weakened therefore voltage stability reaches its limits. In other words, the higher the LBPI value, the shorter the security distance of the network from the point of voltage collapse and vice versa. Hence, the Load Bus Proximity Index (LBPI) is given by

$$0 \leq LBPI \leq 1 \qquad (9)$$

Hence, a load bus with the largest LBPI is the bus most critical within the network. The index (LBPI) suggested in this paper is highly informative and therefore capable of identifying and predicting point of voltage collapse within a network.

3. NUMERICAL EXAMPLES

This section demonstrates the application of the proposed approach using both the IEEE 5-bus system and the practical Nigerian 28-bus network. Single-line diagram of the 5-bus IEEE network is shown in Figure 2 with Tables 1 and 2 showing bus data and line data respectively. Figure 3 shows the one-line diagram of the 28-bus Nigerian network with the details of the network bus and line identifications presented in Tables A1 and A2 in the Appendix.

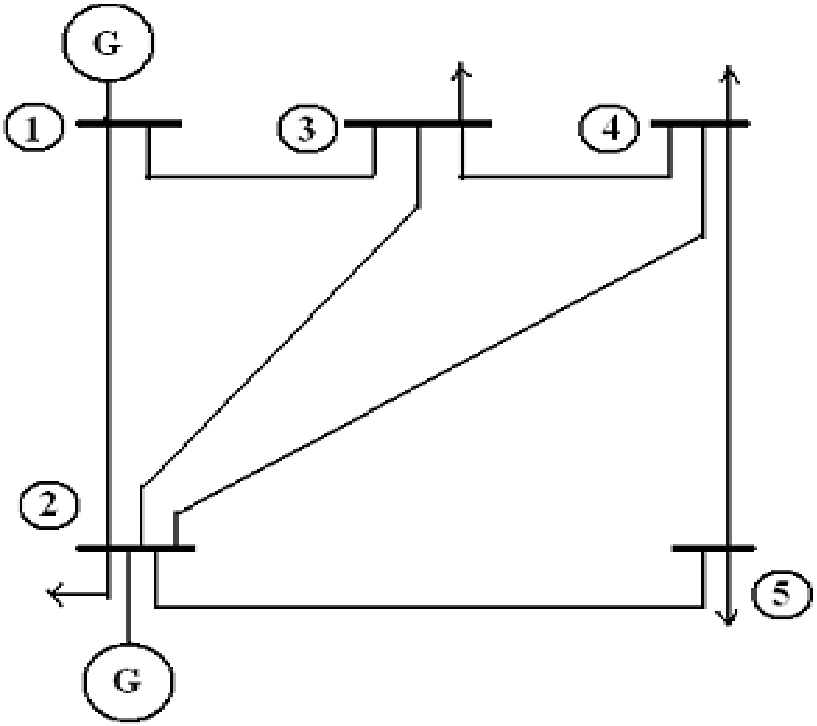

Figure 2: One-line diagram of the standard IEEE 5-bus network

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Table 1: Network bus identification for IEEE 5-bus network

Bus No	Bus Code	Load Demand MW)
1	G1	0.0
2	G2	0.0
3	L3	45.0
4	L4	40.0
5	L5	60.0

Table 2: Network line identification for IEEE 5-bus network

From bus	To bus	Resistance	Reactance	Ground Admittance
1	2	0.020	0.060	0.030
1	3	0.080	0.240	0.025
2	3	0.060	0.180	0.020
2	4	0.060	0.180	0.020
2	5	0.040	0.120	0.015
3	4	0.010	0.030	0.010
4	5	0.080	0.240	0.025

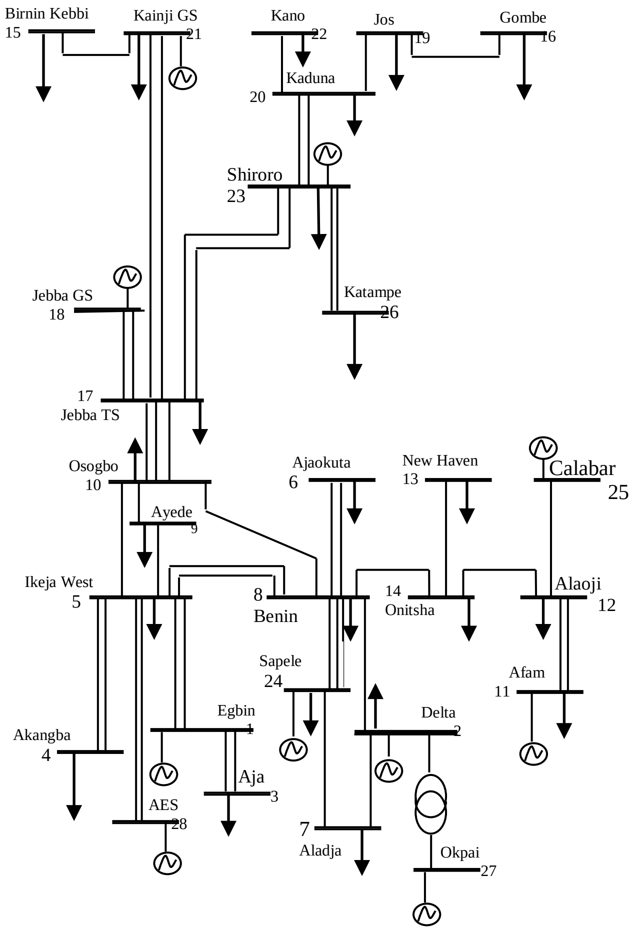

Figure 3: 28-bus Nigerian Grid Network

4. RESULTS AND DISCUSSION

The results obtained, for the two cases considered, are presented and discussed in this section. The results obtained, as presented in this section, are based on the LBPI value for each bus within the network, as given in equation (8).

4.1 Case I: 5-Bus Network

To obtain the LBPI value, the network structural interconnectivity based on the branch admittances is first determined. This is easily captured by the bus admittance matrix of the network. The bus LBPI is then calculated based on the self-admittance of that bus in conjunction with the associated active and reactive power attached to that bus. The numerical values of LBPI obtained at all the buses within the network are then ranked with the bus associated with the highest value of LBPI being the most critical bus in the network, Based on the above explanation, the results obtained, for the $LBPI$ using a simple IEEE 5-bus network, are presented in Table 3. The rankings in Table 5 show the closeness of each bus to the point of collapse with the closest value ranked number 1.

Table 3: Bus ranking based on LBPI for the IEEE network

Bus No	LBPI Value	Ranking
3	**0.233**	**1**
4	0.177	3
5	0.213	2

It can be seen that the highest magnitude of LBPI obtained is 0.233, which corresponds to load bus 3 and is ranked number 1. Therefore, bus 3 is the closest bus to the point of collapse within the 5-bus network and hence it is referred to as the critical bus within the network under study where the reactive power support could be located for proper network operation. Though the system appears to be stable, any slight load increase on bus 3 will tend to lead to collapse. The graphical illustration of the above information is clearly depicted in Figure 4.

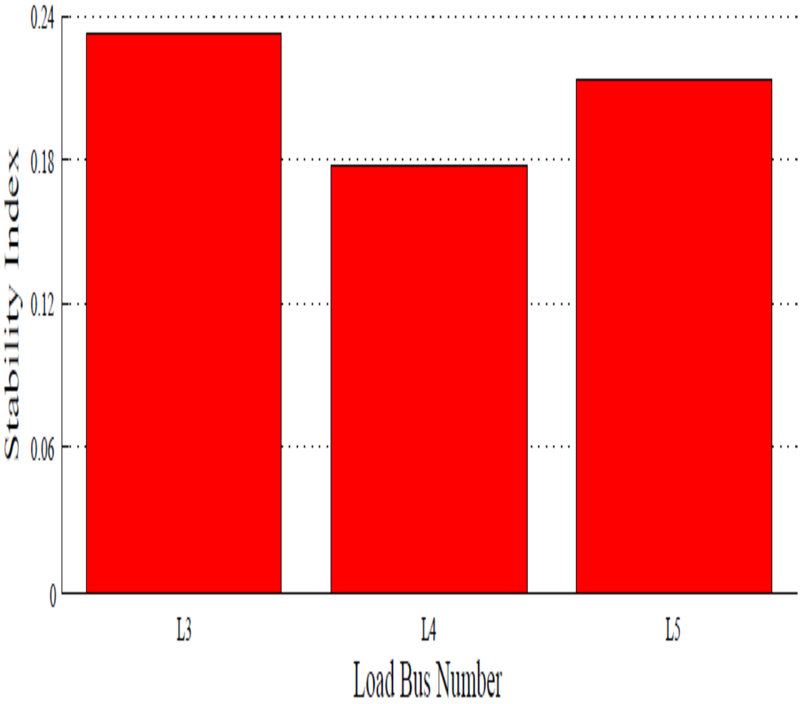

Figure 4: Variation of LBPI with bus number for 5-bus network

4.2 Case II: Nigerian 28-Bus grid Network

Table 4 presents the results obtained with the application of the LBPI approach to Nigerian 28-bus network. The LBPI values obtained for the load buses within the network and their corresponding rankings are presented in the Table 4.

It can be seen that **Jebba TS** with LBPI value of 0.1236 corresponds to the load bus with the highest LBPI value within the network under consideration and it is ranked number 1 . Hence, based on this method, Jebba TS is the critical bus and the closest load bus to the point of network collapse followed by **Jos**, which is ranked number 2. Therefore, for a secure and reliable operation of the network for security purposes, a close monitoring of these buses is highly required. In addition, it can be seen that the bus with the least LBPI value within the network is ranked number 18 corresponding to **Akangba** and is the bus farthest from point of collapse and is the most secured load bus within the practical network under study followed by **Aja TS**. Figure 5 depicts the graphical illustration for the variation of LBPI with respect to network buses.

Table 4: Bus ranking based on LBPI for the Nigerian network

Bus Name	**Bus Code**	**LBPI Value**	**Ranking**
Aja TS	**L11**	**0.0004**	**17**
Akangba TS	**L12**	**0.0001**	**18**
Ikeja West TS	L13	0.0021	12
Ajaokuta TS	L14	0.0222	3
Aladja TS	L15	0.0041	8
Benin TS	L16	0.0046	7
Ayede TS	L17	0.0014	15
Osogbo TS	L18	0.0060	4
Alaoji TS	L19	0.0028	11
New Haven TS	L20	0.0008	16
Onitsha TS	L21	0.0033	10
Birnin-Kebbi TS	L22	0.0054	6
Gombe TS	L23	0.0036	9
Jebba TS	**L24**	**0.1236**	**1**
Jos TS	**L25**	**0.0243**	**2**
Kaduna TS	L26	0.0058	5
Kano TS	L27	0.0017	14
Katampe TS	L28	0.0017	13

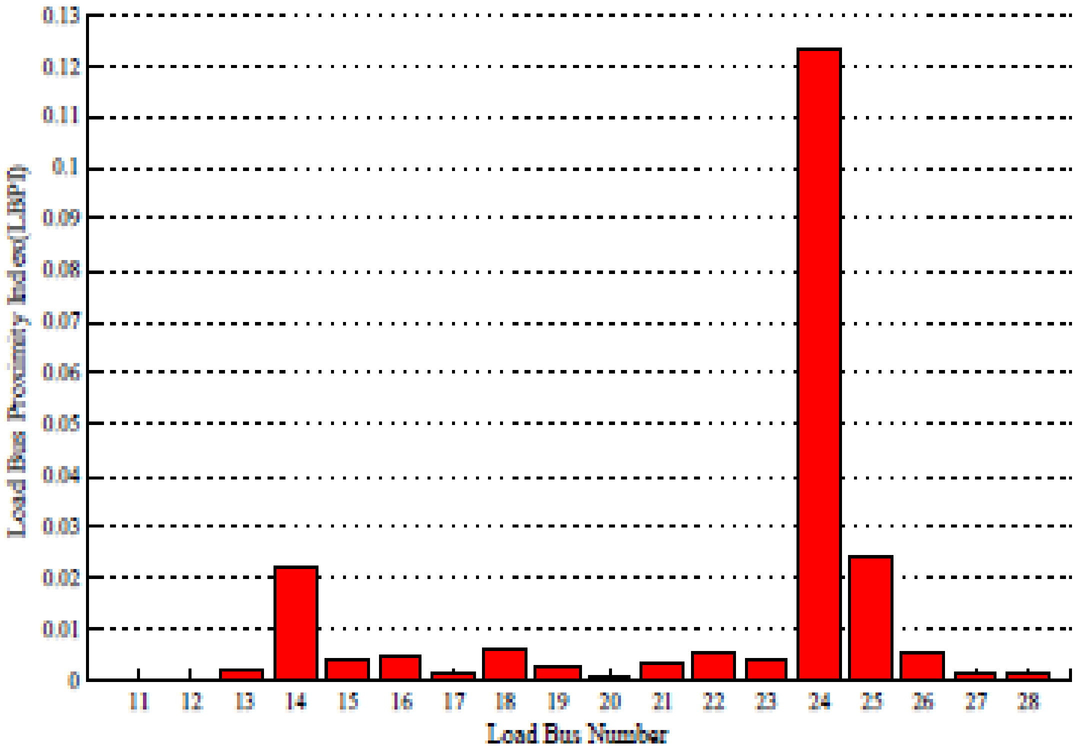

Figure 5: Variation of LBPI with bus number for 28-bus network

5. CONCUSSION

In this paper, a new approach for predicting voltage collapse within practical power networks has been presented. The applicability of the approach on both the standard IEEE network and practical Nigerian power network shows that the approach provides a reliable pointer to the voltage security margin. Compared to other approaches, this model could be useful in making faster decisions for proper network operation most especially for a smarter grid application.

On further investigation, it was found out in the Nigerian network that all those buses ranked numbers 1 to 10 are either in the northern part of the country and/or far from generating stations. This phenomenon signifies the need and importance of ring network. Therefore, there is a need for building more generating stations, where most appropriately needed, to form ring network which will limit the effect of network collapse.

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APPENDIX

Data for the Nigerian 28-bus Network

Table A1: Network bus identification for Nigerian 28-bus network

Bus No	Bus Code	Bus Name	Load Demand (MW)
1	G1	Egbin	68.9
2	G2	Delta	89.0
11	G3	Afam	52.5
18	G4	Jebba GS	0.0
21	G5	Kainji	7.0
23	G6	Shiroro	70.3
24	G7	Sapele	20.6
25	G8	Calabar	0.0
27	G9	Okpai	0.0
28	G10	AES	0.0
3	L11	Aja	274.4
4	L12	Akangba	344.7
5	L13	Ikeja West	633.2
6	L14	Ajaokuta	13.8
7	L15	Aladja	96.5
8	L16	Benin	383.3
9	L17	Ayede	275.8
10	L18	Osogbo	201.2
12	L19	Alaoji	427.0
13	L20	New Haven	177.9
14	L21	Onitsha	184.6
15	L22	Birnin-Kebbi	114.5
16	L23	Gombe	130.6
17	L24	Jebba TS	11.3
19	L25	Jos	70.3
20	L26	Kaduna	193.0
22	L27	Kano	220.6
26	L28	Katampe	290.1

Table A2: Nigerian 28-bus transmission line data

From bus	To bus	Resistance	Reactance	Ground Admittance
3	1	0.0006	0.0044	0.0295
4	5	0.0007	0.0050	0.0333
1	5	0.0023	0.0176	0.1176
5	8	0.0110	0.0828	0.5500
5	9	0.0054	0.0405	0.2669
5	10	0.0099	0.0745	0.4949
6	8	0.0077	0.0576	0.3830
2	8	0.0043	0.0317	0.2101
2	7	0.0012	0.0089	0.0589
2	27	0.0079	0.0591	0.3900
7	24	0.0025	0.0186	0.1237
8	14	0.0054	0.0405	0.2691
8	10	0.0098	0.0742	0.4930
8	24	0.0020	0.0148	0.0982
9	10	0.0045	0.0340	0.2257
15	21	0.0122	0.0916	0.6089
10	17	0.0061	0.0461	0.3064
11	12	0.0010	0.0074	0.0491
12	14	0.0060	0.0455	0.3025
13	14	0.0036	0.0272	0.1807
16	19	0.0118	0.0887	0.5892
17	18	0.0002	0.0020	0.0098
17	23	0.0096	0.0721	0.4793
17	21	0.0032	0.0239	0.1589
19	20	0.0081	0.0609	0.4046
20	22	0.0090	0.0680	0.4516
20	23	0.0038	0.0284	0.1886
23	26	0.0038	0.0284	0.1886
12	25	0.0071	0.0532	0.3800
5	28	0.0016	0.0118	0.0932