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Critical Node Detection for Voltage Collapse Mitigation in Modern Power Systems: A Network Topological-Based Approach

[1]Akintunde S. Alayande, [2]Ignatius K. Okakwu, [3]Olakunle E. Olabode, [4]Musediq A. Sulaiman, [3]Abduulfatai Ibrahim and *[5]Ajibola O. Oyedeji

[1]Department of Electrical and Electronics Engineering, University of Lagos, Akoka, Lagos State, Nigeria
[2]Department of Electrical and Electronics Engineering, Olabisi Onabanjo University, Ago-Iwoye, Ogun State, Nigeria
[3]Department of Electrical and Electronics Engineering, Bells University of Technology Ota, Ogun State, Nigeria
[4]Department of Mechanical Engineering, Olabisi Onabanjo University, Ago-Iwoye, Ogun State, Nigeria
[5]Department of Computer Engineering, Olabisi Onabanjo University, Ago-Iwoye, Ogun State, Nigeria

*Corresponding author's email: oyedeji.ajibola@oouagoiwoye.edu.ng

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Abstract

Quick detection of critical nodes has become a great concern to most investors and utilities recently due to its influence on prevention of the frequent occurrence of voltage collapse within a power network. This paper, therefore presents an option for detecting critical nodes, an approach which is based on the network topological characteristics of power networks. The mathematical formulations of the approach from the basic circuit theory laws were revisited. A Normalized Eigenvalue (NEV) index using eigenvalue and eigenvector analyses was then developed using MATLAB 2019b as the simulation tool. A simple 10-bus network was used to test the effectiveness of the NEV index method suggested in this paper. The NEV for all the network buses was determined and ranked in decreasing value of NEV to measure the criticality and vulnerability of each load node to voltage collapse within the system. Buses 6 had the highest value of NEV index (1.00) while bus 4 had the lowest NEV index (0.00) value. This suggested that there is a possibility of occurrence of over-voltage at bus 6 and under-voltage at bus 4. Therefore, buses 4 and 6 were identified as the critical buses, where placement of the reactive power support will be most beneficial. The results obtained were compared with those obtained using other methods documented in the literature. The comparison showed the effectiveness of the approach in quick identification of critical parts of the network most especially during critical outages.

Keywords: FACTs Devices; Voltage Collapse; Compensation; Instability; Optimization

1. Introduction

Most modern power system networks have experienced frequent voltage collapse recently, which has been a great concern to utilities and researchers globally [1,2]. Voltage collapse often occurs when there is a shortage of reactive power within the network [3, 4]. This is compounded by the continuous increase in the demand for electric energy with little or no compensation in the generation of electric energy. A reliable and secure power system operation, therefore, demands that the voltage profile as well as the system frequency be maintained within specified limits even during contingency situations [5]. In practical power systems, the occurrence of faults is highly inevitable [6, 7]. However, its effect on the power system operations should be adequately and effectively controlled [8]. This is highly required in order to maintain the integrity of the system. The inherent weakness in the network topology and occurrence of disturbance within the network adversely affect the integrity of power systems and the aftermath could be the occurrence of voltage collapse within the system [1,8]. Another main cause of this voltage collapse is the deficiency of reactive power within the system [4,9,10]. Once this happens, the losses within the system increases, the voltage at every node drops below the specified values and the network transfer capability decreases significantly. In order to overcome this challenge, a reactive compensation is highly required such that the voltage magnitude and angle at every node of the system is enhanced and the losses within the system are drastically reduced [11]. Furthermore, total blackout or voltage collapse could be experienced as a result of the occurrence of disturbances within practical power systems [11-14].

The influence of a disturbance on the operation of power system has usually been instability problem and this should be highly minimized if not completely avoided [1,14,15]. Several contingency situations have been experienced and documented in the open literature, within modern power systems, in recent times [8,15-21]. In interconnected power networks, stability is the ability of the networks to return to its normal stable state after experiencing disturbances. Transient stability problem often arises as a result of any unbalance between the system generators and the load, which leads to swinging of the rotor angle of the synchronous machines [13,22-25]. The aftermath is the increasing stress on power systems which, if allowed to be prolonged results in system instability or voltage collapse. The main interest of power system engineers, planners and operators is to ensure quick recovery of the system back to its equilibrium position following large and sudden disturbance [26].

In the quest for resolving this challenge, various power system researchers have deployed various methodologies. The well-known existing method for providing solution to the problem to improve the capacity of the network is network reinforcement [11]. This approach is highly uneconomical as it involves seeking permission for right-of-way as well as some environmental and social constraints. In recent times, research has shown that one simple way of overcoming this challenge is to connect Flexible AC Transmission Systems (FACTs) at suitable load nodes in the power system network [18,24-32]. Installation of these FACTs devices improves the overall capability of the network as well as improving the performance of the existing power network. In order to operate power system economically, these FACTs devices need to be optimally placed within the network. The main bottleneck associated with these existing approaches lies in the identification of the load nodes where the effect of the FACTS placement in the network will be optimal.

The traditional approach to proving a solution to the optimal location of FACTS devices has been through optimization-based approach [18,28,30,33] whose solution could only be obtained iteratively. For example, in [34], the method of Ant Colony Optimization (ACO) was explored to identify the voltage collapse point within power system networks. The study considered two test systems in order to assess the performance of the detection algorithm proposed. The first scenario used a 9-bus system while the other scenario used a standard IEEE 118-bus system. In [35], an evolutionary algorithm was employed to solve the problem of an automatic allocation of FACTs devices for voltage collapse mitigation within power systems. The results obtained demonstrated the effect of FACTs allocation on the voltage stability enhancement. In [36], control of transient stability in power system is considered. The results obtained proved that the system can consistently be stabilized through the use of both the variable parametrized controllers and linear-parameter-varying models of the network nodes. It is however, shown that the size of the power network is proportional to the design effort. Although these optimization-based approaches have been extensively deployed in providing solution to the problem in the open literature they are not without limitations that include, but not limited to, time and space complexity, existence of premature convergence and local optimal solution.

The National blackout or voltage collapse has been a major challenge combating virtually every part of the world in recent times [1,37]. This unpleasant situation is as a result of deficiency of enough reactive power and large variation or unbalance between power generation and power demand within the network [33,38]. Power system instability is a very complex problem that has challenged power system engineers for decades due to its computational complexity and hence requires better and alternative computational tools for its analysis [32]. Based on the foregoing, an alternative approach to solving this problem is, therefore presented in this paper for a reliable and secure power system operation.

The contributions offered by the alternative approach presented in this paper are as follows: first, it eliminates mathematical complexity observed in the traditional methods, which are power-flow-based analyses. Second, the problem of slack bus selection is totally avoided. Another contribution offered by the method suggested in this paper is that it does not involve iterative procedures, which results in high computational savings and hence, it is less time-consuming. In other words, it results in a reduced computational time, and provides for a real-time update of the network.

2. Materials and Methods

2.1 Theoretical Framework and Mathematical Formulations

In a complex infrastructure such as power systems, very few nodes are connected. These inherent properties have two main merits in power system computational analysis. Firstly, the amount of memory required for storing the network data is substantially reduced. There exists an increase in the processing speed for the computations and hence leads to a substantial savings in the computational time. To derive maximum benefits offered by these properties in solving power system problems, Kirchhoff's Current Law is applied. Consequently, the linear relationship between the branch currents and the nodal voltages in an interconnected power network can be expressed as

$$[I]=[Y][V] \tag{1}$$

where $[Y]$ represents the admittance matrix, $[I]$ represents the vector of currents and $[V]$ represents the vector voltages.

Expansion and partitioning of (1) with respect to locations of generator and load nodes give

$$[I_G]=[Y_{GG}][V_G]+[Y_{GL}][V_L] \qquad (2)$$

$$[I_L]=[Y_{LG}][V_G]+[Y_{LL}][V_L] \qquad (3)$$

where $[I_G]$ and $[I_L]$ are the branch currents at the generator and load buses respectively.

$[V_G]$ and $[V_L]$ are the vectors of nodal voltages at the generator and load buses respectively

$[Y_{LL}]$, $[Y_{GG}]$, $[Y_{LG}]$, and $[Y_{GL}]$ are the sub-matrices of $[Y]$.

Algebraic and mathematical manipulations of (2) and (3) can easily be expressed as

$$\begin{bmatrix} V_G \\ I_L \end{bmatrix}=\begin{bmatrix} Z_{GG} & K_{GL} \\ H_{LG} & D_{LL} \end{bmatrix}\begin{bmatrix} I_G \\ V_L \end{bmatrix} \qquad (4)$$

Where,

$$[Z_{GG}]=[Y_{GG}^{-1}] \qquad (5)$$

$$[K_{GL}]=-[Y_{GG}^{-1}]\,[Y_{GL}] \qquad (6)$$

$$[H_{LG}]=[Y_{LG}][Y_{GG}^{-1}] \qquad (7)$$

$$[D_{LL}]=[Y_{LL}]-[Y_{LG}][Y_{GG}^{-1}][Y_{GL}] \qquad (8)$$

Substantial contributions have been made through the use of each of the sub-matrices defined by Equations (5) to (8) for resolving various power system issues in the literature. Some of the applications of these indices can be found [39-42]. However, the application of these indices, in resolving various power system issues such as security assessment and voltage collapse assessment in modern power system with high penetration of distributed energy and power electronics devices, has not been holistically investigated. In this paper, the application of $[D_{LL}]$ in quick identification of the most suitable location of network devices such as reactive power support is revisited. The matrix $[D_{LL}]$ is a square matrix with a dimension of $L \times L$. It captures all the electrical attractions within the load-to-load region with the influence of all generator bus attractions being eliminated. The details on the mathematical formulation can be found in [43-45]**.**

Decompose $[D_{LL}]$ using eigenvalue analysis and substitute into (4). This result to

$$[V_L]=[D_{LL}]^{-1}\{[I_L]-[H_{LG}][I_G]\}=\left[\sum_{k=1}^{n}\frac{v_k\,p_k^T}{\lambda_k}\right]\{[I_L]-[H_{LG}][I_G]\}$$

(9) All symbols have their usual meanings in [45].

By normalizing the elements of the matrix $[D_{LL}]$, the NEV index, for any bus i, can be obtained as follows:

$$[NEV]_i=\frac{[D_{LL}]^{\max}-[D_{LL}]^{original}}{[D_{LL}]^{\max}-[D_{LL}]^{\min}} \qquad (10)$$

Where,

$[D_{LL}]^{original}$ contains the same elements as the original $[D_{LL}]$ matrix, $[D_{LL}]^{\max}$ represents the highest value of the elements in the $[D_{LL}]$ matrix and $[D_{LL}]^{\min}$ represents the least value of the elements in the $[D_{LL}]$ matrix.

It can be seen, from equation (10) that when the element of the $[D_{LL}]^{original}$ matrix is the same as the value of $[D_{LL}]^{\max}$, the $[NEV]$ index becomes 0 and when the element of the $[D_{LL}]^{original}$ matrix is equal to the 1. Hence, the range of operation for the bus i $[NEV]$ index can be written as

$$[NEV]_i^{\min}\le[NEV]_i\le[NEV]_i^{\max} \qquad (11)$$

Where, $[NEV]^{\min}=0$ and $[NEV]^{\max}=1$

Close examination of equation (10) show that the bus associated with the $[NEV]$ value of 1 is the critical bus in the network where a reactive power support can be located to mitigate the influence of voltage collapse in the system.

The load voltage equation, as a function of the network parameters, load and generator currents, in terms of $[NEV]$ index, can therefore be expressed as

$$[V_L]=[NEV]_L\,\{[I_L]-[H_{LG}]\,[I_G]\} \qquad (12)$$

It can be seen from (12) that there is a direct relationship between the load bus $[NEV]$ index and the network load voltage. $[NEV]^{\min}=0$ corresponds to the steady-state operation of the network where there is over-voltage issue and $[NEV]^{\max}=1$ corresponds to the steady-state operation of the network where there is under-voltage issue. Consequently, the two extreme values of the $[NEV]$ index ($[NEV]^{\max}$ and $[NEV]^{\min}$)

correspond to the critical load buses in the network. This information suggests that the optimal benefits will be derived by the network if the reactive power supports are suitably placed as identified by the $\left[NEV\right]$ index. This index gives a useful insight into the structural interconnectivity that exists between the network components and the electrical distances between them. These characteristics allows for easy identification of the suitable load nodes within the system where the reactive power support could be optimally placed to enhance the load bus voltage profile and reduces the total losses within the system. The normalized version of the Coupling Strength Index (NCSI) proposed by the authors of [46] is also explored in this paper for comparing the results obtained using the two approaches. This is demonstrated through the numerical illustration presented in the section that follows.

2.2 Illustrative Example

Consider the one-line diagram of an equivalent Southern Indian 10-bus system shown in Figure 1 [40]. It consists of 12 transmission lines, three generator nodes 1 to 3 respectively and load nodes 4 to 10. The transmission line data for the network is presented is adapted from [47]. All simulations are carried out using MATLAB 2019b.

3. Results and Discussion

In this section, the effectiveness of the approach suggested in this paper is illustrated using a simple 10-bus network shown in Figure 3.1. The results obtained are presented, discussed and compared with the results obtained from various existing methods.

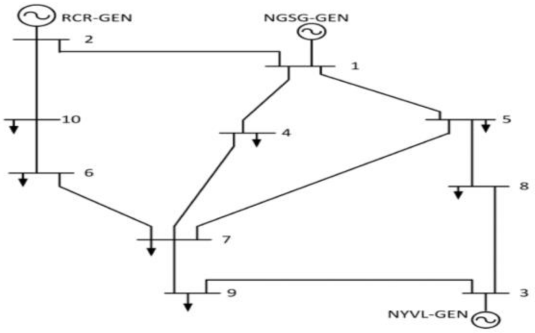

Figure 3.1: The Equivalent Southern Indian 10-Bus Network [40].

3.1 Normalized Eigenvalue Index-Based Approach

Based on the concept of the eigenvalue and eigenvector analyses as explained in section 2, a direct relationship exists between the network voltage profile and the $\left[NEV\right]$ index at the network load nodes. At the maximum value of $\left[NEV\right]$ index, the network operates at a steady-state load voltage below the prescribed $\pm 5\%$ of nominal voltage value (over-voltage) and at the minimum value of $\left[NEV\right]$ index, the network operates at a steady-state load voltage below the prescribed $\pm 5\%$ of nominal voltage value (under-voltage). Consequently, any load node with a voltage value below or above the prescribed voltage limits is liable to voltage collapse.

In identifying the critical load nodes where the reactive power supports such as Flexible Alternating Current Transmission Systems (FACTS) devices could be placed to mitigate voltage collapse in the network, the network bus admittance is first calculated from which the network $\left[D_{LL}\right]$ is captured. Next, eigenvalue decomposition is then applied on the matrix $\left[D_{LL}\right]$ and the results are then normalized to determine the $\left[NEV\right]$ index for all the load buses. The calculated NEV index for all the load buses are ranked in descending or ascending order of priority. The load node associated with the highest magnitude of $\left[NEV\right]$ index having a value of 1.0 is the load bus whose voltage is above the prescribed nominal voltage value (over-voltage). Similarly, the load node associated with the lowest magnitude of $\left[NEV\right]$ index having a value of 0.0 is the load bus whose voltage is below the prescribed nominal voltage value (under-voltage). Hence, load buses whose calculated values of $\left[NEV\right]$ index are 1.0 and 0.0 are identified as the most critical and influential load nodes where the influence of reactive power support placement on the network operation could be made significant.

The results obtained based on the $\left[NEV\right]$ index approach was presented in Table 3. 1. As can be seen from the Table, the $\left[NEV\right]$ index values have its magnitudes ranging from 0 to 1.

Table 3.1: Critical Load Node Identification Based on Normalized Eigenvalue Index Method

Load Bus No.	NEV Index	NEV Index Ranking
6	1.0000	1
10	0.8700	3
9	0.8215	5
8	0.7349	7
7	0.6335	6
5	0.4780	4
4	0.0000	2

Based on the foregoing, it can be seen that NEV Index of 1.0 is associated with bus 6 and it is ranked number 1. This means that under a light load operation of the network, bus 6 may experience over-voltage problem and it is therefore liable to voltage collapse problem. The implication of this is that a reactive support device could be placed at bus 6 to enhance the voltage profile and mitigate the effect of voltage collapse in the network. Furthermore, it can also be seen that NEV Index of 0.0 is associated with bus 4 and it is ranked number 7. This means that under a heavy load condition, bus 4 may experience under-voltage problem and could therefore be liable to voltage collapse problem. This means that bus 4 is an optimal location for the placement of a reactive support device in order to enhance the voltage profile and mitigate the influence of voltage collapse in the system.

Based on the results obtained using the NEV index, buses 4 and 6 can therefore be said to be the influential load nodes within the network where the placement of the network devices such as FACTS devices would be highly beneficial to the network.

3.2 Normalized Coupling Strength Index-Based Approach

From the results obtained based on NEV index, it has been shown that both buses 4 and 6 have a significant influence on the voltage instability or collapse of the equivalent Southern Indian 10-bus network. The Normalized Coupling Strength Index (NCSI) approach is used to also identify the most critical bus in order to corroborate the results obtained using NEV index. The results of the critical load bus identification based on the Normalized Coupling Strength Index (NCSI) are presented in Table 3.2. According to the formulation of CSI based on the theory of network structural characteristics, the higher the value of the load node CSI, the higher the force of attraction that binds such a node to the network and vice-versa for a load node with the least magnitude of normalized CSI.

The bus ranking is then carried out based on the value of the normalized CSI in an ascending order of the normalized CSI magnitude but a descending order of priority. That is, the most priority load node is associated with the normalized CSI value of 0 and it is ranked number 1. Similarly, the least priority load node is associated with highest value of normalized CSI (1.0) and it is ranked number 7 as shown in Table 2. Consequently, according the concept of NCSI, the bus associated with the highest magnitude of NCSI (1.0) is identified as the least priority load bus while the bus associated with the least normalized value of CSI (0.0) is the most priority load bus. Based on the foregoing, the most priority load bus is bus 6 as it ranked number 1 while bus 4 is ranked number 7 being the most highly coupled bus to the network according to NCSI.

Table 3.2: Critical Load Node Identification Based Normalized Coupling Strength Index Method

Load Bus No.	NCSI	NCSI Ranking
6	0.0000	1
10	0.9106	3
9	0.9406	4
8	0.9881	6
7	0.2991	2
5	0.9518	5
4	1.0000	7

3.3 Comparison of Various Approaches

The results obtained through various methods are compared with the method NEV and NCS indices suggested in this paper as presented in Table 3.3. The results obtained from each method are presented in accordance to the order of severity of each load node in the network. The results presented in Tables 3.1 and 3.2 are summarized in columns 2 and 4 while the results obtained through the use of Reactive Power Loss Index (RPLI) [48], Q-V sensitivity based on modal analysis [49] and Continuation Power Flow (CPF) [50] methods are presented in columns 6, 8 and 10 respectively. Figure 3.2 shows the graphical illustration of the five methods presented in Table 3.3 for the sake of comparison.

Table 3.3: Critical Load Node Identification Based Normalized Coupling Strength Index Method

Load bus	NCS Index	Priority Order	NEV Index	Priority Order	RPLI [69]	Priority Order	Q-V [70]	Priority Order	CPF [71]	Priority Order
6	0.0000	1	1.0000	1	5.2538	1	0.3875	1	0.56425	1
10	0.9106	3	0.8700	3	0.5416	7	0.0772	5	0.77201	6
9	0.9406	4	0.8215	5	2.8143	4	0.0926	4	0.72015	4
8	0.9881	6	0.7349	7	2.415	6	0.0159	7	0.81755	7
7	0.2991	2	0.6335	6	4.172	2	0.2272	2	0.61605	2
5	0.9518	5	0.4780	4	2.4187	5	0.0723	6	0.72078	5
4	1.0000	7	0.0000	2	2.8588	3	0.1273	3	0.6585	3

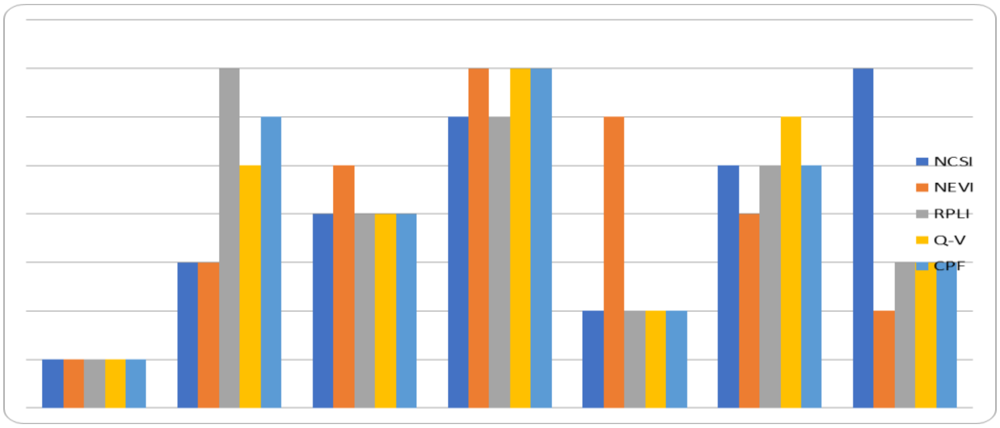

Figure 3.2: Comparison of Different Approaches Based on Severity Order of The Network Load Buses.

As seen in Table 3.3, it is observed that all the methods identified load bus 6 as the most critical load bus within the system. Therefore, in order to enhance the operation of the system, bus 6 is the optimal location where a reactive power support should place.

4. Conclusion

In this paper, various techniques through which the location of network devices for effective operation of power system could be achieved have been holistically reviewed. Various challenges associated with the existing approaches have been critically highlighted. A topologically-based approach from the circuit theory laws has been suggested as an alternative approach to solving the voltage collapse problems in power systems. The results obtained are compared with the existing approach with a strong agreement between the results. The results obtained from this study provide useful information which could be of great help to the system operator and planners in accurate determination of optimal points where the location of FACTs placement will be most beneficial. In addition, it will be helpful to the system operators since it will provide them with adequate information as to controlling and monitoring of the operation of a practical power system during normal and abnormal situations. It will also assist in quick determination of the stability margin for practical power systems.

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