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A Comparative Study of the Prediction of Voltage Collapse in Power System Network

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Abstract

Instability of the power system voltage often results in voltage loss and /or the system collapse, which is a problem for operators and users of power networks. This work presents a stability index suitable for examining the Power System Networks (PSNs) voltage condition. The measure, known as the ABCD Line Stability Index (ABCD_LSI), is derived from a transmission line's two port network and ABCD parameters using the π-model. It is therefore necessary to treat the equation of the transmission line in the form of complex power and voltage. The goal of the ABCD_LSI index was to predict the voltage collapse of a power system network and also to identify the weakest, associated critical bus lines with respect to a bus for the optimal placement of compensation devices and to investigate the effect of increasing reactive power loading on the PSN. The developed index is then compared to the existing Lmn and Fmn line stability index and was tested on the IEEE 14-bus system using a program coded in the MATLAB environment. The three indices were then simulated for the base case and the contingency- variation of the reactive loads in the network. For the base case, the IEEE 14-bus test system was stable with all the three indices approximately s<1 for all the lines, but it was observed that the new developed index (ABCD_LSI), did not give exact values of the other two indices Lmn and FVSI since the other indices did not consider the length variation of the transmission line in its formulation of their stability index. And this makes the ABCD_LSI more feasible than the other indices even though the other two existing indices could also determine the Voltage stability index of a line.

Keywords: Voltage Collapse, Power System Network, Stability Index, Power System Stability, Voltage Stability

INTRODUCTION

In recent years, the demand for electrical energy has increased rapidly with no corresponding increase in generation has posed a serious challenge. The number of system blackouts in the past decade attest to the fact that more work still need to be done to tackle the problem of voltage instability and resultant voltage collapse especially in large scale power system [1], [2].Voltage instability in Power System Network (PSN) occurs when a disturbance on the network causes a gradual and uncontrollable line in voltage. This disturbance can be a form of continuous loading of the system which will pull it to a condition of voltage instability and this has posed a great challenge in power system utilities [3]. In today's world, Modern Power system is a compound structure interconnected with network elements which are prone to failure when the system is heavily load and hence result to the drop-in voltage level thereby give rise to voltage instability. In this project research, an extensive literature review of various papers has been done on various approaches for predicting voltage collapse. Most researchers has used different methods in predicting the proximity of a power system to voltage collapse, such methods include: The use of New line stability index [1], a monitoring and predicting frame work (critical transition approach) [2], structural inherent characteristics approach [3], Generalized regression neural network (GRNN) approach[4] , Modal analysis technique for the prediction of voltage stability [5] and various other methods had been proposed. In this project, the proposed index developed would be comparisons would be made. MATLAB software will be used in programming this mathematical formulation and would predict the voltage instability tested with IEEE 5-bus power flow results.

The developed stability index would be compared with the two existing indices, discussions and inferences would be drawn from the comparison. Also, conclusions recommendations would be made. The voltage stability problem is now a serious concern in the electric utility industry, and other areas of power systems. Many large interconnected power systems are increasingly experiencing abnormally high or low voltages and voltage collapse. The voltage collapse are associated with the increased loading transmission lines, insufficient reactive power supply, and the transmission of power over long distances [3].The problem of voltage instability has been a great concern to me because almost everything we use in Life needs a power source, our day-to-day activities requires electric power, either for the operation of our industrial machine, home appliances or to power our electronic gadgets for academic learning. This study is carried out to predict the voltage instability using ABCD Line parameter and comparing the results with two existing approaches which are the Lmn and FVSI approaches, and MATLAB software is used as a programming tool to encode this mathematical formulations to be used to detect voltage instability. The bus and line data obtained from the 5bus system is inputted into the software to predict the shortest distance to voltage collapse thereby reducing the voltage instability in PSNs, this method will provide a more accurate and faster result, because the software is to be programmed to give the voltage collapse point which is done in little or no time. The significance of this study is that the voltage collapse problem can be avoided in the electric industry and other power system networks since we can determine the likelihood of power failure or voltage instability so that the knowledge of a balanced load system can be attainable in order not to have declination in voltage level along the transmission line. The importance of this study to an individual and the society at large is to be able to detect the time range in which a power system will experience failure, that is to know when there will be power blackouts, so that alternative source of power can be provided during this power outage. The relevance of this study to me even as a student researcher is to enable me to develop my skills in using Matlab software to solve voltage instability problem in PSN. ABCD line parameter approach will be used to derive the line stability index and the index would be tested using a simulated IEE 5-bus system on MATLAB R2016a. . in Addition, This project is restricted to the study of voltage stability and the prediction of voltage collapse in PSN with the aid of line stability index developed. This research is centered on the prediction of voltage collapse using a line stability index based the ABCD line parameter of a transmission line.This project helps us to identify the critical line, the most stable line, the weakest bus with respect to a reference bus so that we can determine where to place the compensation device and voltage collapse relay on the PSNs and to examine the effect of increasing reactive power on the power system network. The derived index was tested on the simulated model of the IEE 14-bus system for validation of the index. The simulations of this research was carried out in the MATLAB, R2016a, (64-bit) environment. The aim of this research is to examine and predict voltage collapse in Power System Network. And the objectives are to derive the ABCD line stability index suitable for predicting voltage collapse in PSN and also the proposed derived index would be investigated on the MATLAB environment and the se oftware on the simulation of The IEEE 5-bus system and the results are compared to existing stability indices for the validation of proposed stability index. The results of the proposed ABCD_LSI would be tabulated and compared to the existing indices Lmn and FVSI. The voltage stability index was simulated on MATLAB, R2016a, (64-bit) environment using the data generated for the IEE 5-bus system.

Literature Review

Many authors have contributed in various ways in providing a quick solution to voltage collapse in power systems Networks and most of these approaches were conventional in nature. For instance, the authors in [1], proposed a voltage line stability index that is suitable for the prediction of voltage collapse in PSN. They utilized the new line stability index_1 (NSL_1) technique which combines two voltage existing indices: the Line Stability Index (Lmn) and the Fast Voltage Stability Index (FVSI), taking advantage of their accuracy and speed. The use of the new line stability index_1 (NLSI_1) was tested on the IEE 14_bus system on both cases and the result obtained was equal to the results of the other two indices Lmn and FVSI. The result showed that the new line stability index (NLSI_1) is valid and accurate since it corresponds to the result obtained for the IEE bus system [1]. The major bottleneck in implementing this method is that it uses a repetitive power flow solutions and this requires a lot of time. A novel method to monitor and predict the voltage collapse called the Critical Transition Approach was proposed in [2]. In this method, the theory of critical transition and its connection with power system voltage collapse were presented in a general fast show dynamic system. The authors also used theoretical deviation to show that as the system approaches collapse point, the variance of the state variable deviation increases monotonically. The work utilized the scaling law between the driving parameter and the variance which has been derived to predict the transition point.

This simplified the prediction of futuristic collapse point [2]. The uniqueness of this paper is that it uses a data-driven method instead of the model based method mostly used by different authors which is affected by the model accuracy. The limitation of this approach is that it is not applicable to complex power systems, and also this approach cannot figure out the relations among variance ofdifferent state variable which could help identify critical generators and make this approach applicable to the controlled design. In [3], the researchers proposed the approach of voltage stability index (VSI) and the inherent structural characteristics (ISCT) to predict voltage instability in power system. In this approach, the IEEE 6 and the IEEE 5-bus system were used to demonstrate their effectiveness [3]. This approach initially used voltage stability index, which is solely based on running repetitive load flow solutions while finding the point that is prone to system voltage collapse and that the limitation of this method is that it is time consuming as discussed in [1], thereby they further considered the inherent structural characteristics approach which only requires a single computation of the eigen values of the matrix WLL as this method does not require repetitive running the traditional power flow and can easily give the information of the strength of the network . The formulations are done based on basic circuit theory laws. MATLAB software package was the tool used for simulations in this paper and the result of this simulation shows thatvoltage collapse point is easily and quickly detected and predicted with the approach of inherent structural characteristics [3]. The GRNN (Generalized Regression Neural Network) technique in predicting voltage collapse risk index due to transmission line outage for power system security monitoring was proposed byauthors in [4]. In this approach, the risk of voltage collapse was measured by considering the L- index as the impact of voltage collapse while Poisson probability was used to model the probabilityof the transmission line outage. This method was facilitated using an Artificial intelligence in GRNN network, its spread value is determined using the CS (cuckroo search) optimization technique. The effectiveness of the proposed method was validated by comparing the performanceof GRNN-CS with GRNN-heuristic method in which its spread value is gotten by trial and error method. The result shows that the proposed method has better performance than the heuristic method with 13.1% reduction in error, thereby improving the risk prediction assessment [4]. The authors in [5] presented the application of the continuous Tellegen's power flow to the voltage stability problem. The proposed method is tackled using the conventional load flow equations, classical Newton's Raphson method and Tellegen's equations, the improper choosing of the step size is a major disadvantage of this method. The proposed method and the conventional method was tested on the IEE bus test system and the result of the proposed method obtained was the same as the continuous power flow when the size control was decreased, the accuracy of the proposed method is more dependent on the step size control and the lesser the step size control, the accuracyof the result [5]. A modal analysis technique was recommended by authors in [6], which provides both a relative proximity to voltage instability of the system and also identify the key contributing factors contributing to instability. In this method of modal analysis technique, useful factors such as power flow analysis and traditional V-P/V-Q analysis has been included. The result showed that after testing this modal analysis technique on the IEE 30 bus system, the technique was shown to provide an exact estimate of the system's proximity to the voltage instability and it could also predict the weakest buses and the critical buses in the transmission line [6]. An intelligent System (IS) strategy which has been recognized as a reliable approach to facilitate real-time DSA in [7]. Although most literature research work concentrate on the rotor angle stability problem. The research work focuses on a dynamic insecurity phenomenon- the short termvoltage instability, which comprises of a fast and complex load dynamics. The problem was modelled into a classification sub problem for transient voltage and a prediction sub problem for unacceptable dynamic voltage. A hierarchical IS was developed to address the two sub problems sequentially. The IS was implemented in an offline training, a real time application, and an online updating pattern and is based on ensemble learning of random-weights neural networks. The simulation results on the New England 39-bus system verify its superiority in both learning speedand accuracy over some state-of-the-art learning algorithms [7].

The authors propounded a regression tree-based approach to predicting the power system stabilitymargin and detecting impending system event in [8]. The objective of this paper is to examine the efficiency of the RT system in detecting oscillatory stability margin and power system voltage. It began with the theoretical fundamentals of stability margin and instability detection after which the RT based evaluation scheme was proposed. The result shows that the PMU measurements are quickly processed by the RT model, and it easily handles measurement errors that are within 1% TVE. The conclusions obtained was the input features of the regression tree (RT) were synchronized voltage and current phasors which can predict the voltage stability behavior and thesystem oscillatory with a high rate of accuracy and the RT sensitivity to system topology variationis less pronounced in complex network and under slight changes in topology [8]. From the paper in [9], the authors presented Methods used for estimating and predicting imminent stability losses together with underlying concepts. The approach does not require a previous knowledge of specific metadata and also at the node of the observed grid does it need detailed models in observing the current power flow. A voltage control is also not required; however, thisdoes not restrict the applicability of the current method, so far the reactive power used for controlis included in the observed load flow at the node under observation. Findings from both numericalsimulations and experiments in a real power system are presented. Our data fusion studies show a clear indication of the collapse with regression and PCA close to the operating point. Signs of an impending collapse, though hardly recognizable from the voltage alone, are observed in the generated graphs using this data fusion. It was discovered that the analytical solutions and results from numerical simulations tally the trend. Some large deviations observed between the results from such approaches and the real-life measurements indicate the importance of field tests to validate these data fusion models [9].

The voltage stability margin was propounded by the authors in [10], which was defined as the distance from a given power profile to the boundary of the stability region, was effectively estimated using a data-driven machine learning approach. By using continuation power flow and SDP power flow methods, a set of operating points that are inside and outside the feasibility region of AC power flow equations yet are close to the stability boundary were obtained respectively. Based on these generated operating points, the boundary of the potentially non convex voltage stability region was learnt by a trained neural network classifier with a hinge loss at the output. The resulting score metric obtained at the output layer of the neural network before thresholding,was shown to be an excellent indicator of the voltage stability margin were used to train an end- to-end stability margin estimator for an arbitrary operating point. The performance and computational advantage of the proposed approach are verified by numerical experiments, and oneof the key advantage of this proposed method is its speed [10].

A novel voltage stability index referred to a line used to rank the line outage contigency was presented in [11]. This index help to identify the critical line in a system. A line is considered to be critical if the voltage stability index referred to this line closes to 1.00. This index is then furtherused in determining the contingency ranking which is based on the line outage in a system. The contingency ranking process can be conducted by computing the line stability index of each line for a particular line outage and sort them in descending order. Line outage which resulted in voltage instability is ranked the highest. Therefore the contingency ranking could assist the operating engineer to take necessary actions in order to avoid the occurrence of voltage collapse in the system if actual line outage were to occur in the respective line. The contingency ranking can be utilized **as** an alarm indicating to prevent voltage collapse and cascading blackouts [11].

A voltage stability index which is built based on machine learning techniques to avoid voltage collapse situation had been presented in [12]. The main impact was to obtain a novel stability predictor by comparing three different machine learning algorithms neural network, linear regression and decision tree which are trained using three different dataset considered on different voltage indices (FVSI, Lmn and NLSI) used in [1], for each algorithm that gave rise to nine predictors. The best result was obtained based on A.N.N algorithm trained by NLSI dataset. An early warning system and maneuver algorithm was built by the predictor which can handle the voltage stability phenomenon under the system operator supervision [12]. According to the authors in [13], a new index for voltage collapse prediction which was based onthe changing ratio of the reactive loss of the system was presented. The index was used only for information obtained directly online, and a little calculation was used for the online purpose. Theefficiency of the proposed index was proven based on test results obtained on the modified two- area system. The index is highly effective and suitable for on-line voltage prediction [13]. An online model for predicting voltage collapse in power systems was developed in [14]. In the research work, evaluating the system voltage stability at a bus only requires information on the voltage phasor and angle information at a bus and the network admittance matrix in the form of voltage collapse prediction indexes. These indexes can be used to predict the power system voltage collapse by the central load dispatch centres, and they also serve as a tool to initiate corrective actions. These techniques was tested for different IEEE test systems and the results simulation of the IEEE-118 bus system was presented. The method was computationally effective and appropriate for real time prediction of voltage collapse. An online implementation of the techniqueusing UCA was proposed [14].

The authors in [15], presented a study on various voltage stability indices which was carried out on two conventional networks of electrical power system which are WSCC 9 bus system and IEEE 118 bus system by varying all loads equally until the system becomes unstable. The results obtained showed that the WSCC 9 bus system collapses when the system load is 2.5pu = 2.5 × (315MW, 115MVAR) = (787.5MW, 287.5MVAR), whereas the IEEE 118 bus system becomes unstable when the system load is 2.7pu = (11453.4MW, 3883.6MVAR). The conclusion reached was the voltage collapse prediction index (VCPI) was a better index than other voltage stability indices in detecting the proximity the system was towards becoming unstable [15]. A system for real-time prediction and mitigation of voltage collapse in the natal network of the Eskom power system was propounded in [16]. The mitigation and prediction system utilizes synchrophasor data to generate the power system state. After which the voltage collapse indices was obtained using its network and state data, and it shows the proximity to voltage collapse and optimal load shedding schemes was suggested. The proposed system relies on power system state measurement and fast power flow analysis to assess voltage stability. The system is suitable for real-time implementation without any further simplifications. In the simulation of the Eskon power system model, critical buses and problematic conditions were efficiently located [16]. In Ref. [17], the authors proposed a new application of the Least Error Square (LES) estimation algorithm for the prediction of voltage collapse in a power system using the local measurement of the current and voltage of a load bus. Utilizing these measurements, a polynomial of order n was assumed for the association of the load current and load voltage, hence the KVA. The LES estimation algorithm was used to generate an approximate value for the coefficient of thepolynomial. The point where the load acquires its highest apparent power (volt-ampere) for the bus gives the collapse point. The method was far better than the conventional load flow method asit avoids the process of repetitive load flow. The proposed algorithm was tested on the IEEE-30 bus system and compared with the conventional load flow methods [17]. In Ref. [18], the research focuses on a new method for predicting dynamic voltage collapse in power systems by proposing a new indicator called the power transfer stability index (PTSI) calculated at a bus. The index was used to give information on voltage stability on voltage instability caused by disturbances in the system. Power system dynamic models was used in the dynamic simulation of voltage collapse where the three machine, nine-bus test system and 39-testbus system were used in carrying out simulations for dynamic voltage collapse. Power system analysis tool box (PSAT) was used as the programming tool for simulation. The simulation result showed that the performance of the proposed power transfer stability index (PTSI) was very sensitive in detecting dynamic voltage collapse because the PTSI approaches closely to unity during a collapse condition. Hence, the PTSI was considered to be a more accurate indicator compared to the VCPI indicator for the voltage collapse prediction [18].

A novel approach to voltage collapse using a probabilistic predictor-detector that depends on a conditioned probabilistic quadratic line voltage stability index coined as q-LVSI and a moving average filter coined pq-LVSI for deductive analysis of power system network state was focused by the authors in Ref. [19]. The associated rules for logical analysis used to detect and estimate a collapsing signal from those of q-LVSI estimates were presented. The resulting q-LVSI values was filtered and enhanced by the moving average filter consisting of short term and long term prediction before probabilistic logical analysis takes place. MATLAB was the programming tool used. The results obtained showed that the long term filter will promptly detect the line that has greater chances of experiencing voltage collapse when there is a differential in the lag and lead parameters. Hence, this approaches allows for ascertaining voltage collapse before it occurs [19]. In Ref. [20], the paper summarizes a methodology for detecting voltage collapse by utilizing regularized least square classification algorithm (RLSC) and was used to correspond future system voltage abnormality and the dynamic system responses. PSSE dynamic simulation tool was used to simulate the stressed cases for dynamic response and predict system voltage abnormality in future time after the incidence of specific contingencies using the RLSC method. Data processing and feature extraction was done and the pattern recognition technique was utilized to predict voltage collapse stability from power system dynamic response. Furthermore, the researchers determined the prominent features and parameters in classifying voltage normal and voltage abnormal cases from dynamic simulation data. The method of this approach was compared with the methods that are based on steady state and snapshot analysis, the proposed method had provision for cases in which voltage instability is generated by generator and load system dynamics system dynamics and the different load characteristics and generator dynamics had been added to the modeling of the system [20]. In Ref. [21], this paper aims at a novel method for discovering of remained time to voltage collapse utilizing virtually acceleration of OLTC's as the most crucial determinant in voltage instability cases. The proposed method can be applied to long term voltage instability due to both load event and contingencies and it is a real time method. The results obtained adequate performance of the proposed algorithm in both speed and accuracy of estimating time to voltage instability. Conclusively, this approach provide a good approximation for the remained time to voltage instability occurrence in order to make decisions based on time using an alternative. The method was easy to understand and can simply be implemented for any desired system [21].

An invariant which predicts the proximity of voltage collapse in a smart grid system was proposed in [22]. The invariant is based on real time online monitoring parameters. The efficiency of the invariant method in predicting voltage collapse had been carried out using experimental simulations. It was seen that the voltage collapse occurs due to insufficient reactive power supply in the system as the reactive power to keep the subsystem voltage stable within acceptable value, increases with increased in loading at the buses. The bottleneck of this approach is stated as if the the droop generator was absent, the system would crash at a much lower load. Thus, further work need to be done to explore what modifications can be implemented on the existing indicator to perform when state measurements might not be present for different reasons [22].In Ref. [23], the authors discussed on the prediction of voltage collapse in power system. Their work aims at understanding the structure associated with voltage collapse and its prediction. Algorithms for the prediction of the critical point are derived using static analysis approach. The method is based on a general ABCD network, therefore can be implemented in power systems with short transmission line, medium length transmission line or long distance transmission line. A numerical example was also presented [23].

Ref. [24], this paper focuses on a salient pole generator capacity used as a case study in a four bus interconnected network and in a simple radial system. The EMTDC/PSCAD software was used to feature indices of voltage instability under different simulation conditions for both systems. The simulation results showed that the generator capacity was an estimate of the reactive power, the excitation voltage and the power angle. From the two cases studied, the prediction of voltage are characterized by indices which are: load reactive power, the excitation voltage, and the component of the source reactive power and the V/Q ratio of the load [24]. bIn Ref. [25], this paper utilized a novel stability constrained optimal power flow (VSC-OPF) approach based on static line voltage stability indices and reduce power system losses under stressed and contigency condition. The approach proposed used a voltage collapse proximity indicator (VCPI) to predict the closeness of the system to voltage collapse. The method was validated on the standard IEE30- bus and 57-bus test system under different conditions and the results was compared with the two VSC-OPF methods based on the minimum singular value and the bus voltage indicator L-index. The simulated result also showed that the proposed VSC-OPF was effective based on the voltage stability index [25].

Voltage Stability Indices

There are varieties of tools for assessing whether a system is voltage stable or not and how close the system is to instability. These tools are called voltage stability indices. These indices help thesystem planner and operators to know the condition of voltage stability in a power system. They indicate how close the system is to voltage collapse or instability. The indices should be simple, easy to implement and computationally inexpensive. The indices expose the critical bus of a powersystem and the stability condition of each line connected between two buses in an interconnectednetwork [1]. In general, the analysis of the voltage stability problem of a given PSN should:

1. Determine the system's proximity to collapse.
2. Establish when the voltage instability could occur.
3. Identify the weak buses in the PSN.

Existing Voltage Collapse Indices

The P-V Curve and Q-V Curve

The P-V curves are used to determine the loading margin of a power system. Figure 1 shows a P-V diagram of a power system at a particular operating point, with the two solution points. The upper VU is the normal operating point, but a solution at VL is also possible. It can be seen that thedistance (ΔV) between the two solutions tends to zero as the margin of power Pm between the operating point and the point of maximum power approaches zero. The Q-V curve can be used asan index for voltage instability, the point where dQ/dV is zero is the point of voltage stability limit.Figure 2 shows the Q-V curves for a bus in a particular power system for three different loads: P1, P2 and P3. [1]. The vertical axis shows the amount of additional reactive power that must be injected into the bus to operate at a given voltage. The operating point is the intersection of the power curve with the horizontal axis, where no reactive power is required to be injected or absorbed [1].

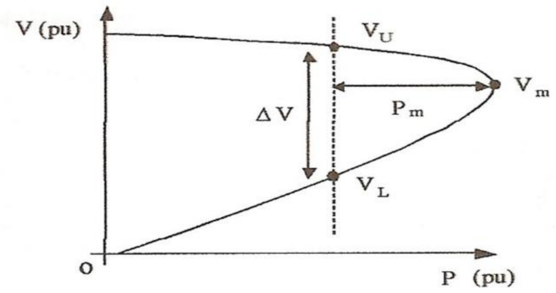


Figure 1: P-V curve [1]

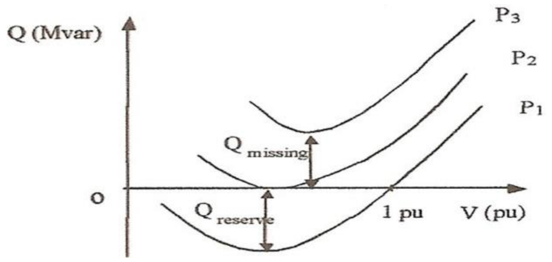


Figure 2: Q-V curves for three loads [1]

Modal Analysis

The voltage stability of a power system may be deduced from a consideration of the eigenvalues and eigenvectors of the system's reduced power-flow Jacobian matrix [1]. Such eigenvalues are associated with system voltage modes as well as the reactive power variation. In the steady-state, a power system is said to be voltage stable if all the eigenvalues of the reduced power-flow Jacobian matrix are positive and if any of the eigenvalues is negative, then it is [1]. For the reduced power flow Jacobian matrix, a zero (0) eigenvalue means that the system is on the borderline of voltage collapse. It implies that there is a likelihood of voltage instability situation [1]. The PV and QV, the modal analysis and energy-based methods as proposed in [1] are computationally tedious, rigorous and time consuming whereas time is of essence when dealing with voltage collapse prediction. So, the use of less tedious, computational fast and easy-to-use voltage stability indices for online and offline prediction of voltage collapse are preferred.

L- Index (L)

Kessel and Glavitsch, in [1] developed L-index based on the power flow solutions. It measures the proximity to voltage instability and it is appropriate for constant power load type. Its value rangesfrom zero (0) – no load to unity (1) collapse point [1].

L-index is given as:

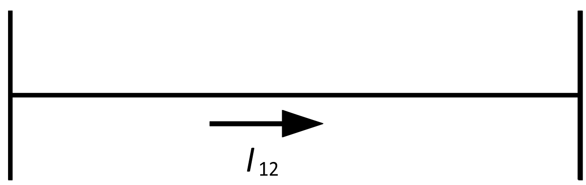
$$L = \max_{j \in \alpha L}\{Lj\} = \max_{j \in \alpha L}\left\{\left|1 - \frac{\sum_{i \in \alpha_G} F_{ji} * V_i}{V_j}\right|\right\}$$

$$F_{ji} = |F_{ji}| \angle \theta_{ji}$$

where L is the set of consumer nodes and G is the set of generator nodes, Lj is a local indicator that determines the busbars from where collapse may originate (Kessel and Glavitsch,). The [F] is computed using $[F] = [YLL] - 1[YLG]$, where $[YLL]$and $[YLG]$ are sub-matrices of the Y-bus matrix. the voltages Vi and Vj are voltages at buses i and j respectively [1].

Line Stability Index (Lmn)

Line stability index (Lmn) is derived based on power transmission line concept in a single line. Moghavvemi and Omar (1998) in [1] derived this line stability index to evaluate the stability of the line between two buses in an inter-connected system reduced to a single-line network as shown in figure 3



$S_s = P_s + jQ_s$ $\qquad$ $S_r = P_r + jQ_r$

Figure 3: Typical one-line diagram of transmission line.

where, Vs, Ps and Qs are the sending-end voltage, real power and reactive power, are respectively. Vr, Pr and Qr are the receiving-end voltage, real power and reactive power respectively. δ1 is the sending-end voltage phase angle and δ2 is the receiving-end voltage phase angle, I12 is the line current and $ is the transmission line angle.

The power flow through a transmission line using pie (π) model representation for a two-bus system is used and the discriminant of the voltage quadratic equation is set to be greater than or equal to 0 (zero). If the discriminant is less than 0 (zero), the roots will be imaginary suggesting that there is instability in the system.

(2.2)

$$Lmn = \frac{4XQ_r}{|V_s|^2 \sin^2(\theta - \delta)} \leq 1$$

The line index is also directly related to the reactive power and indirectly related to the active power through the voltage phase angle δ. A line in the system is said to be close to instability when the Lmn is close to one (1). On the other hand, if the Lmn value is less than 1, then the system is said to be stable [1].

Fast Voltage Stability Index (FVSI)

This index, proposed in [1], is also based on the concept of power flow through a single line. It was developed based on the measurements of voltage and reactive power. In its derivation, the sending bus is taken as the reference bus with the voltage phase angle set to zero. FVSI is a line index derived from the general equation for the current in a line between two buses, labeled 's' and 'r'. Its mathematical expression is given as

(2.3)

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

where Z is the line impedance, X is the line reactance, Q_r is the reactive power flow to the receiving end and V_s is the sending-end voltage. The line whose stability index value is closest to unity (1) will be the most critical line of the bus and may lead to the whole system instability [1]. The evaluated FVSI also helps to determine the weakest bus in the system. The most critical bus in thesystem is the bus with smallest permissible load [1].

Line Stability Factor (LQP)

The LQP index derived in [1] is obtained using the same concept in which the discriminant of thepower quadratic equation is set to be greater than or equal to zero. Figure 3 illustrates a single line of a power transmission concept used in the formation of the index. The line stability factor for this model is reproduced as

$$LQP = 4\left(\frac{X}{V_s^{\,2}}\right)\left(\frac{X}{V_s^{\,2}} p_s + Q_r\right) \quad (2.4)$$

where X is the line reactance, Q_r is the reactive power flow to the receiving bus, V_s is the voltage at the sending bus and P_s is the active power flow from the sending bus. For stable system, the value of LQP index should be maintained at less than 1, otherwise, collapse is imminent [1].

Line Voltage Stability Index (LVSI)

This index is a line voltage stability index that brings to bear the relationship between line real power and the bus voltage [1]. The index fails if the resistance of the transmission line is very closeto zero. The index is formulated as:

$$LVSI = \frac{4RP_r}{V_s \cos\theta - \delta} \leq 1 \quad \textbf{(2.5)}$$

where

$\theta = \tan^{-1} XX$ is the transmission line angle and R is line resistance R

LVSI is more sensitive to δ since cos(θ-δ) is faster than sin(θ-δ) around 90^0 and a healthy line could be identified as a critical line (Haruna, 2015).

New Line Stability Index-1 (NLSI-1)

The NLSI-1 stability index was derived by Isaac Samuel in [1]. To derive the New Line Stability Index-1 (NLSI-1) who first consider the Line Stability Index (Lmn) and the Fast Voltage Stability Index (FVSI) proposed in [1]. We then showed that the FVSI is an approximation of the Lmn and proceed to derive the NLSI-1 for improved accuracy and speed.

$$NLSI\_1 = \frac{4Q_r}{|V_S|^2}\left[\frac{(|Z|)^2}{X}\sigma - \frac{X}{\sin^2(\theta-\delta)}(\sigma - 1)\right] \leq 1 \qquad \sigma = \begin{cases} 1 & \delta < \delta_c \\ 0 & \delta \geq \delta_c \end{cases} \quad (2.6)$$

Note that δ is used here as a modifier.

where 'σ' is a switching function whose value depends on whether the angle difference, δ, is verysmall or not. A large voltage angle difference between two load buses indicates a heavily loaded power system network with large power flows or increased impedance between the load buses. Dobson reported that in a simulation of the grid carried out before the August 2003, Northeastern blackout showed increasing angle differences between Cleveland and West Michigan, revealing that large angle differences could be a risk signal to the occurrence of blackout or system collapse[1]. Therefore, the voltage angle difference, delta 'δ' cannot be totally ignored as done in the mathematical formulation of FVSI. When NLSI_1 is less than 1, the system is stable. The closer its value approaches one (1), then system is unstable and near voltage collapsed.

METHODS

In this SECTION another approach index, ABCD Line parameter stability index, is proposed for the voltage collapse in PSN. The mathematical formulation for the proposed index is given in this chapter. The method and materials used in this study are also presented.

Existing Indices of the Lmn and FVSI Approach

The Line Stability Index (LMN) was proposed by Moghavvemi and Umar, (1998) and the Fast Voltage Stability Index (FVSI) proposed by Musrin and Rahman, (2002). We then showed that the FVSI is an approximation of the Lmn and proceed to derive the ABCD_LSI for it is easy to calculate, less prone to error, and it conforms to the existing Lmn and FVSI. Consider the one-line diagram of a transmission line system. All parameters and variables are in per unit.

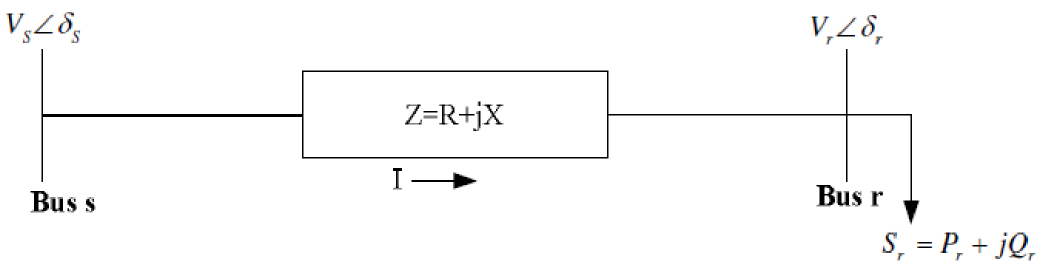


Fig 4 (a): One-line diagram of a typical transmission system

From the above Fig 4(a), bus 's' is the sending end bus which is chosen to be the reference bus whereas bus 'r' is the receiving end bus.

The parameters are defined as follows:

Ss = apparent power at the sending end bus 's' Sr = apparent power at the receiving end bus 'r'

Ps and Pr = sending end real power and receiving end real power respectively Qr = reactive power at the receiving bus 'r'

Vs, Vr = are the voltage angles of the sending end and the receiving end buses respectively.

Z = R+jX is transmission line impedance

Where R is the line of Resistance

X is the line reactance

Using the concept of power flow in the line and analyzing the π-model representation, the powerflow at the receiving end of the PSN shown in Fig 3.1(a) is given as:

Sr = Pr + jQr 3.1(a)

The complex power S, the real power P, and reactive power Q is shown in the power triangle inthe power triangle in Fig 4

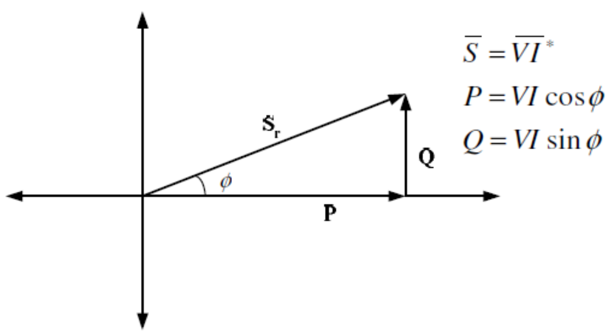


Fig 4(b): The power triangle

From,

$Sr = VrIr^*$ 3.1(b)

Where $I_r = \frac{Vs<\delta s - Vr<\delta r}{z<\theta}$ 3.1 (c)

$\tan\theta\theta = \frac{XX}{R}$

using equation 3.1(c) in 3.1(b) gives:

$$S_r = Vr<\delta r \left[\frac{Vs<-\delta s - Vr<-\delta r}{z<\theta}\right]$$

Therefore, the Line stability index is obtained as:

$$Lmn = \frac{4XQ_r}{|V_s|^2 \sin^2(\theta - \delta)} \leq 1 \qquad (3.2)$$

The FVSI proposed by Musrin and Rahman (2002) hinges on the principle of power flow througha single line for a typical transmission line. It is derived from the voltage quadratic equation at thereceiving-end bus of the two-bus system transmission line model shown in Figure 3.1(a). It is derived from the current flowing in the transmission line to get the voltage quadratic equation. The current, *I* flowing in the network of Fig 3.1(a) is given as:

$$I_r = \frac{V}{XX} = \frac{Vs<\delta s - Vr<\delta r}{z<\theta} \qquad (3.3)$$

But the power at the receiving end is given bySr

$= V_r I_r^*$

Current at the receiving end is given by

$$I_r = \frac{Sr^*}{Vr^*} = \frac{Pr - jjjjr}{Vr<-\delta r} \qquad (3.4)$$

Using equation (3.3) in (3.4) gives

$$\frac{Pr - jjjjr}{Vr < -\delta r} = \frac{Vs < \delta s - Vr < \delta r}{z < \theta} \quad (3.5)$$

Therefore, the Fast Voltage Stability Index is given as:

$$FVSI = \frac{4 Q_r Z^2}{X V_s^2} \leq 1 \quad (3.6)$$

Derivation of ABCD Voltage Prediction Index

Voltage stability deals with the ability of a transmission line to remain under normal operating condition after the removal of disturbance on a PSN, the indices that revealed the proximity of a transmission line to voltage collapse has become an important tool for voltage stability examination and monitoring by power system personnel. These indices can be used for offline or online monitoring in order to predict the closeness to voltage instability. A large section of power system networks deals in the transmission of electrical power from one point to another. However, it is salient for power system engineers to be thorough with the mathematical modelling of how this power is transmitted. ABCD parameters and a two port- network is used to simplify these complex calculations

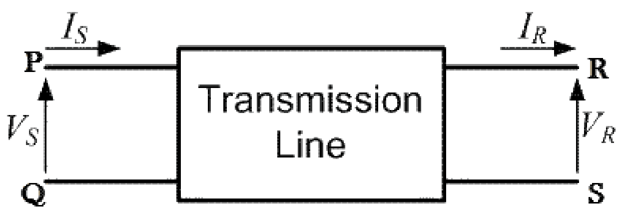


Fig 5 Two port-network

Since Loads are more often expressed in terms of real (Watts/KW) and reactive power (Var/KVar) power. Hence, it is ideal to deal to deal with transmission line equation in the form of sending endand receiving end complex power and voltage.

Let us consider the receiving end as the reference phasor (VR = | VR | <0), and sending end voltage lead it by an angle δ ($V_s = |V_s| \angle\delta$).

The complex power leaving the sending end and entering the receiving end of the transmission line can be expressed on per phase basis as

$$S_R = P_R + jQ_R = V_R I_R^*$$

$$S_S = P_S + jQ_S = V_S I_S^* \quad (3.7)$$

A transmission line on a per phase basis can be regarded as a two port network, where the sendingend voltage Vs and current Is are related to the receiving end voltage VR and current IR, through the ABCD line parameters as expressed by:

$$\begin{pmatrix} V_S \\ I_S \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_R \\ I_R \end{pmatrix} \quad (3.8)$$

From (3.2),

$$B I_R = V_S - A V_R$$

$$I_R = \frac{1}{B} V_S - \frac{A}{B} V_R \quad (3.9)$$

Substitute (3.3) into (3.2)

$$I_S = C V_R + D \frac{1}{B} V_S - \frac{A}{B} V_R$$

$$I_S = \frac{D}{B} V_S - \frac{AD}{B} V_R + C V_R$$

$$I_S = \frac{D}{B} V_S - V_R \frac{AD}{B} - \frac{C}{1}$$

$$I_S = \frac{D}{B}\left[V_S - V_R \frac{AD-BC}{B}\right]$$

Hence,

$$I_S = \frac{D}{B}\left[V_S - V_R \frac{1}{B}\right] \quad (3.10)$$

$$I_S = \frac{D}{B}\left[V_S - V_R \frac{1}{B}\right] \quad (3.10)$$

Let A, B, D, the transmission line constants be written as

$A = |A| < a_1, B = |B| < \beta_1, D = |D| < a_1$ (since A = D)

$$I_R = |\frac{1}{B}| |V_S| <(\delta - \beta_1) - |\frac{A}{B}| |V_R| \leq(a_1 - \beta_1) \quad (3.11)$$

$$I_S = |\frac{D}{B}| |V_S| <[(a_1 + \delta) - \beta_1] - |\frac{1}{B}|| V_R | <-\beta_1 \quad (3.12)$$

$S_R = V_R I_R^*$

$$S_S = V_S I_S^* \quad (3.13)$$

$V_R = |V_R| <0^\circ$

$VS = | VS | < \delta$

This implies that:

$S_R = |V_R|<0^\circ [|\frac{1}{B}| |V_S| <(\delta - \beta_1) - |\frac{A}{B}| |V_R| \leq(a_1 - \beta_1)]^*$

$S_R = |V_R| <0^\circ [|\frac{1}{B}| |V_S| <-(\delta - \beta_1) - |\frac{A}{B}| |V_R| <-(a_1 - \beta_1)]$

$$S_R = \frac{|VR| |VS|}{|B|} < (\beta_1 - \delta) - |\frac{A}{B}| |VR|^2 \leq(\beta_1 - a_1) \quad (3.14)$$

In the same manner,

$S_S = |V_S|< \delta |\frac{D}{B}| \left[V_S <[(a_1 + \delta) - \beta_1] - |\frac{1}{B}| |V_R| <-\beta_1 \ ^*\right]$

$S_S = |V_S|< \delta |\frac{D}{B}| \left[V_S <-[(a_1 + \delta) - \beta_1] - |\frac{1}{B}| |V_R| <\beta_1\right]$

$$Ss = = \left|\frac{D}{B}\right| |V_S|^2 < (\beta_1 - a_1) - \frac{|VR|\,|VS|}{|B|} < (\beta_1 + \delta) \qquad (3.15)$$

Expressing equation (3.7) into Real & Imaginery part

$$P_R = \frac{|VR|\,|VS|}{|B|} \cos(\beta_1 - \delta) - \left|\frac{A}{B}\right| |VR|^2 \cos(\beta_1 - a_1) \qquad (3.16)$$

$$Q_R = \frac{|VR|\,|VS|}{|B|} \sin(\beta_1 - \delta) - \left|\frac{A}{B}\right| |VR|^2 \sin(\beta_1 - a_1) \qquad (3.17)$$

where A $< a_1$ & B $< \beta_1$ are transmission line constants.

For the usual π- model, the transmission can be written as

$$A = 1 + \frac{ZY}{2}$$

$$B = Z$$

Z is the total series impedance of line,

Y is the total line charging susceptance

For a long line transmission line,

$$A = 1 + \frac{Z'Y'}{2}$$

$$B = Z'$$

$$\text{where } Z' = z\left[\frac{\sinh \gamma l}{\gamma l}\right] \qquad (3.18)$$

$$\frac{Y'}{2} = \frac{Y}{2}\left[\frac{\tanh \frac{\gamma l}{2}}{\frac{\gamma l}{2}}\right] \qquad (3.19)$$

Z is the total series impedance of line,

Y is the total line charging susceptance

For a long line transmission line,

$$A = 1 + \frac{Z'Y'}{2}$$

$$B = Z'$$

where $$Z' = z\left[\frac{\sinh \gamma l}{\gamma l}\right] \qquad (3.18)$$

$$\frac{Y'}{2} = \frac{Y}{2}\left[\frac{\tanh \frac{\gamma l}{2}}{\frac{\gamma l}{2}}\right] \qquad (3.19)$$

γ is the propagation constant $\gamma = \sqrt{yz}$ and l is the length of the transmission line.Recall

from (3.9) & (3.10)

$$P_R = \frac{|VR|\,|VS|}{|B|}\cos(\beta_1 - \delta) - \left|\frac{A}{B}\right| |VR|^2 \cos(\beta_1 - a_1)$$

$$Q_R = \frac{|VR|\,|VS|}{|B|}\sin(\beta_1 - \delta) - \left|\frac{A}{B}\right| |VR|^2 \sin(\beta_1 - a_1)$$

This can be re-written as:

$$P_R + \left|\frac{A}{B}\right| |VR|^2 \cos(\beta_1 - a_1) = \frac{|VR|\,|VS|}{|B|}\cos(\beta_1 - \delta) \qquad (3.20)$$

$$Q_R + \left|\frac{A}{B}\right| |VR|^2 \sin(\beta_1 - a_1) = \frac{|VR|\,|VS|}{|B|}\sin(\beta_1 - \delta) \qquad (3.21)$$

Squaring and adding both sides of the equation, thereby eliminating δ, thereby we obtain the locus of P_R against Q_R to be a circle with given values and for assumed values of $|VR|$ *and* $|VS|$ shown as follow:

$$\{P_R + \left|\frac{A}{B}\right| |VR|^2 \cos(\beta_1 - a_1)\}^2 + \{Q_R + \left|\frac{A}{B}\right| |VR|^2 \sin(\beta_1 - a_1)\}^2 = \left\{\frac{|VR|\,|VS|}{|B|}\right\}^2 \qquad (3.22)$$

Since $\cos^2(\beta_1 - \delta) + \sin^2(\beta_1 - \delta) = 1$

If the k^{th} bus is the sending end bus and the m^{th} bus is the receiving end bus and expanding equation (3.22)

$$P_m^2 + \frac{A2}{B2} V_m^4 \cos^2(\beta_1 - a_1) + 2 P_m \frac{A}{B} V_m^2 \cos(\beta_1 - a_1) + Q_m^2 + \frac{A2}{B2} V_m^4 \sin^2(\beta_1 - a_1) + 2 Q_m \frac{A}{B} V_m^2 \sin(\beta_1 - a_1) = \frac{Vk2Vm2}{} \qquad (3.23)$$

Justaposing equation (3.23), we obtain

$$V_m^4 - \left[\frac{Vk2}{A2} - 2\frac{B}{A} P_m \cos(\beta_1 - a_1) - 2\frac{B}{A} Q_m \sin(\beta_1 - a_1)\right] V_m^2 + (P_m^2 + Q_m^2)\frac{B2}{A2} = 0 \qquad (3.24)$$

Let $m = V_m^2$

$$m^2 + bm + c = 0 \qquad (3.25)$$

solving equation (3.25) quadratically; where

$$b = -\left\{\frac{Vk2}{A2} - 2\frac{B}{A} P_m \cos(\beta_1 - a_1) - 2\frac{B}{A} Q_m \sin(\beta_1 - a_1)\right\};$$

$a = 1$;

The results obtained for V_m should have real roots, for the system to be stable.

For real roots,

$b^2 - 4ac \geq 0$

$b^2 \geq 4ac$; i.e $1 \geq \frac{4ac}{b2}$ i.e $\frac{4ac}{b2} \leq 1$

$\frac{\sqrt{4ac}}{b} < 1$

$$\frac{2\sqrt{ac}}{b} \leq 1 \qquad (3.26)$$

Equation (3.25) gives the condition of the voltage line stability index,

$LS_i = \frac{2\sqrt{(Pm2 + Qm2)} \, [illegible]}{[illegible] \; A2} \leq 1$

$LS_i = \frac{2 [illegible] (Pm2 + Qm2)}{[illegible] Pm \cos(\beta 1 - \alpha 1) - 2 \frac{B}{A} [illegible]} \leq 1 \qquad (3.27)$

Where LSi is termed as voltage stability index of the line Pm and Qm are the real and reactive power received at the receiving end m, A = |A| <a1, B = |B| < β1 are the transmission line constants, Vk and Vm are the sending end bus k voltage and the receiving end m voltage respectively. At or nearcollapse point, voltage stability index of any one or more lines approaches one (1). This method derived is used to assess the voltage stability of a PSN.

Flow Chart Diagram

The flowchart diagram of the Line voltage stability index is shown as below

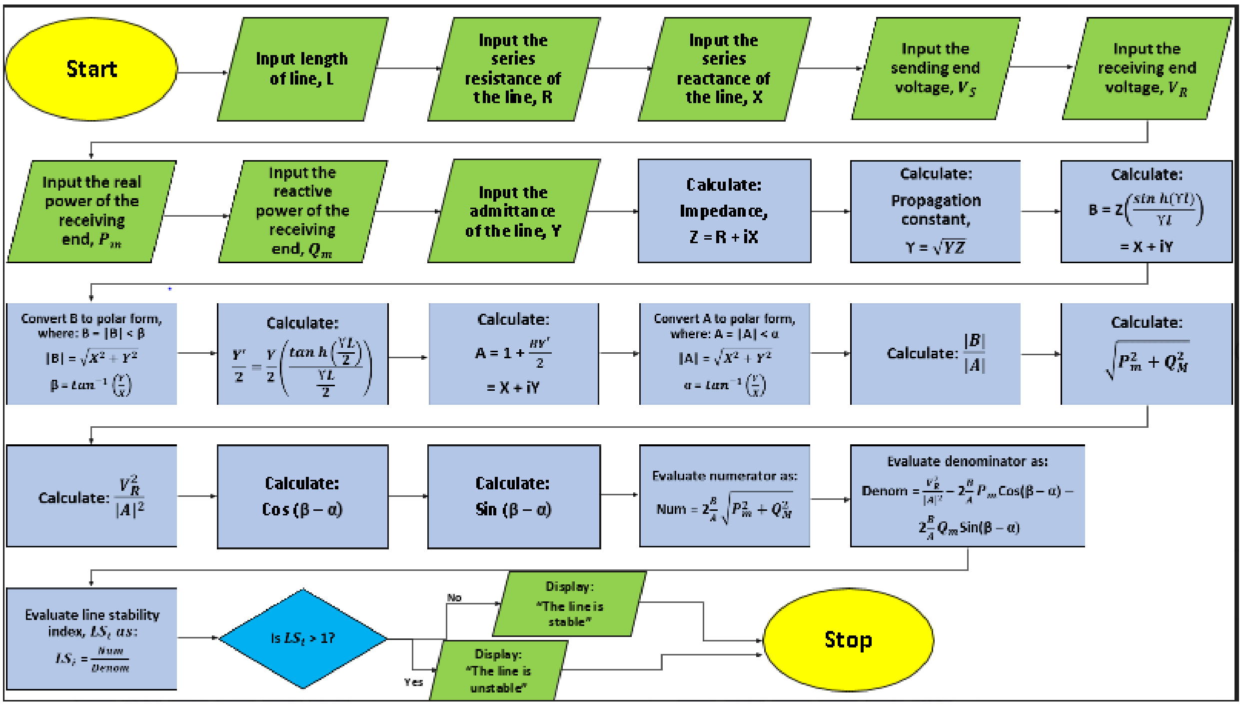


Fig 6 Flowchart diagram of the developed ABCD_LSI

METHODS

MATLAB programming software will be used as a tool for calculating the Line Stability Index ofany transmission line between two buses in a power system network, where one of the buses serves as the generator bus or the sending end bus while the other bus is the receiving end bus.

Algorithm

Step 1: Input the length of line, L

Step 2: Input the series resistance of the line r Step 3: Input the series impedance of the line x

Step 4: Input the sending end voltage Vs

Step 5: Input the receiving end voltage VR

Step 6: Input the Real Power of the receiving end Pm

Step 7: Input the Reactive Power of the receiving end Qm

Step 8: Input the admittance (total line charging susceptance) of the line YStep 9: Calculate the total series impedance Z, using z = r+jx

Step 10: Calculate the propagation constant γ using $\gamma = \sqrt{yz}$

Step 11: Calculate B using $B = Z' = z \frac{\sinh \gamma l}{\gamma l}$

Step 12: convert to polar form, which takes the form $B = |B| < \beta 1$

Step 13: Calculate the $\frac{Y'}{2}$ using $\frac{Y'}{2} = \frac{Y}{2}\left[\frac{\tanh \frac{\gamma l}{2}}{\frac{\gamma l}{2}}\right]$

Step 14: Calculate the constant A, using $A = 1 + \frac{Z'Y'}{2}$

Step 15: convert to polar form, which takes the form $A = |A| < a1$

Step 16: Calculate $\left|\frac{B}{A}\right|$

Step 17: Calculate $\sqrt{(Pm2 + Qm2)}$

Step 18: Calculate $\frac{Vk2}{A2}$

Step 19: Calculate $\cos(\beta 1 - a\ 1)$

Step 20: Calculate $\sin(\beta 1 - a\ 1)$

Step 21: Calculate the Line stability index LSi, using the formula derived as

$$LSi = \frac{2\frac{B}{A}\sqrt{(Pm2 + Qm2)}}{\frac{Vk2}{A2} - 2\frac{B}{A} Pm \cos(\beta 1 - a1) - 2\frac{B}{A} Qm \sin(\beta 1 - a1)}$$

Step 22: If $LSi \leq 1$, then the line is stable ELSE unstable

The case study used in this research is the IEEE 5-bus test system for the index validation'

The IEEE 5-Bus Test System

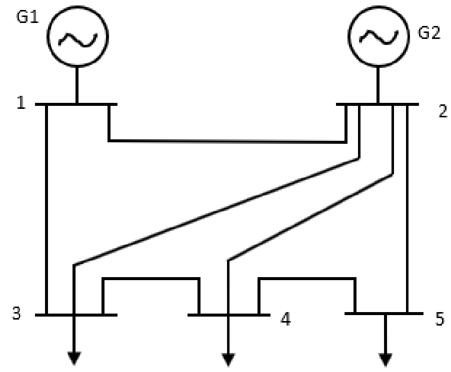


Fig 7: One-line diagram of an IEEE 5-Bus Network

The single-line diagram of IEEE 5-Bus network s shown in Fig 7. The transmission line parameters, generation, and loads are given in per unit value. The network details are: Number oflines = 7, Number of buses =5, Number of generators = 2, out of the generator buses, bus 1 is theslack bus and Number of loads = 4.

IEEE 5-Bus System Data

Table 1 Bus data of the IEEE 5-Bus Network

Bus Code P	Assumed Bus Voltage	Generation		Load	
		Megawatts	Megavars	Megawatts	Megavars
1	1.06 + j0.0	0	0	0	0
2	1.0 + j0.0	40	30	20	10
3	1.0 + j0.0	0	0	45	15
4	1.0 + j0.0	0	0	40	5
5	1.0 + j0.0	0	0	60	10

Table 2 Line data for the IEEE 5-bus Network

Bus Code p – q	Line impedance Z_{pq}		Line charging Y_{pq} / 2
	R per unit	X per unit	
1 – 2	0.02	0.06	X per unit
1 – 3	0.08	0.24	0.0 + j0.025
2 – 3	0.06	0.25	0.0 + 0.020
2 – 4	0.06	0.18	0.0 + j0.020
2 – 5	0.04	0.12	0.0 + j0.015
3 – 4	0.01	0.03	0.0 + j0.010
4 – 5	0.08	0.24	0.0 + j0.025

RESULTS

In section 3, material and methods were presented and the voltage stability index ABCD-LSI wasderived accordingly. This study presents comparison of case studies of the ABCD index to the existing Lmn and FVSI, as to validate the ABCD-line index. The Simulations are carried out on the IEEE 5-bus system.

Simulations

Simulations are carried out based on the following scenarios:

1. The base case: This is the normal operational mode.
2. The contingency case: This is the variation of the reactive power of load busesfrom the base case one at a time.

Base case results of the IEEE 5-Bus System

The data used to test ABCD_LSI approach was obtained from standard IEEE 5-bus system as shown in Table 1 and Table 2 and the same data was used to calculate the stability index of theexisting Lmn and FVSI approach.

Table 3 shows the base case values of the line stability indices. Figures 8 shows the barchartsof the Lmn, FVSI and ABCD against line number i.e the seven (7) interconnected lines of the IEEE 5-bus system.

Table 3. The base case results for the IEE 5-bus system

Line No.	From Bus	To Bus	Lmn	FVSI	ABCD_LSI
1	1	2	0.047466	0.047466	0.011071
2	1	3	0.1424	0.1424	0.20726
3	2	3	0.15864	0.15864	0.068542
4	2	4	0.04	0.04	0.084012
5	2	5	0.053333	0.053333	0.049525
6	3	4	0.0066667	0.0066667	0.0061429
7	4	5	0.10667	0.10667	0.26854

At base case the simulations were carried out to obtain the stability indices: Lmn, FVSI, ABCD using equations 3.2, 3.6 and 3.27 respectively. The MATLAB code used for the indices are shownin appendix A. From Table 4 and Figure 8, the system is stable as none of the indices of each line is near 1. It is observed that the three indices' values are less than 1 which shows that each ofthe line is stable. This validates that the **ABCD_LSI** can be used in place of the other two indicesto calculate the line stability index.

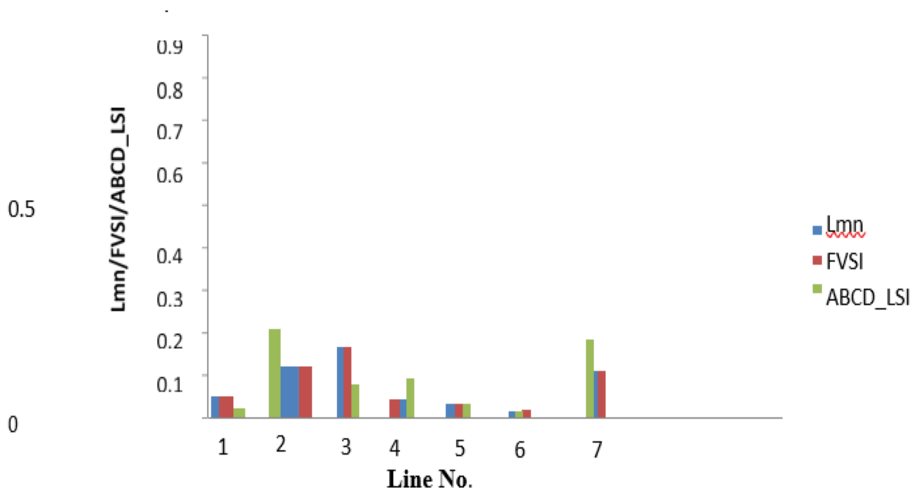


Fig 8 The barchart of the Lmn, FVSI, and ABCD_LSI Vs Line Number for the basecase.

Simulation Results for the Contigency Analysis

The contingency considered is the variation of the reactive power demand. This is carried out to determine the maximum loadability and critical line by varying the reactive load on the load buses until the value of the index approaches 1. The load bus reactive power was varied one by one to examine the total reactive power on all load buses. This was done to determine the load capacity limit on each load bus, the bus ranking was performed to classify the weak bus and critical lines with respect to a bus using the voltage stability indices that fit when the voltages are unstable. Theweakest bus is described as the bus with a low-limit of load-ability and a margin of stability of lowvoltage. This is the bus which needs mitigation equipment, or a solar PV generator, and/or voltage collapse relay to avoid and reduce the failure or instability of the voltage.

The simulation results tabulated in Table 4 is for the determination of the maximum reactive load for all the load buses on the IEEE 5-bus system.

Table 4. Maximum Load for the Load Buses

Bus 3						
From	**To**	**Lmn**	**FVSI**	**ABCD_LSI**	**Ranking**	**Max Load (MVAr)**
2	3	1.0047	1.0047	0.16491	1	**0.95**
1	3	0.90186	0.90186	0.34166	2	
3	4	0.12667	0.12667	0.015501	3	

Bus 4						
From	**To**	**Lmn**	**FVSI**	**ABCD_LSI**	**Ranking**	**Max Load (MVAr)**
4	5	1.0027	1.0027	0.36059	1	**0.94**
2	4	0.752	0.752	0.18853	2	
3	4	0.12533	0.12533	0.015365	3	

Bus 5						
From	**To**	**Lmn**	**FVSI**	**ABCD_LSI**	**Ranking**	**Max Load (MVAr)**
4	5	1.0027	1.0027	0.36059	1	**0.92**
2	5	0.50133	0.50133	0.091929	2	

Graphical User Interface Designed for the MATLAB CODE used to test for the Threeindices: Lmn, FVSI and ABCD_LSI

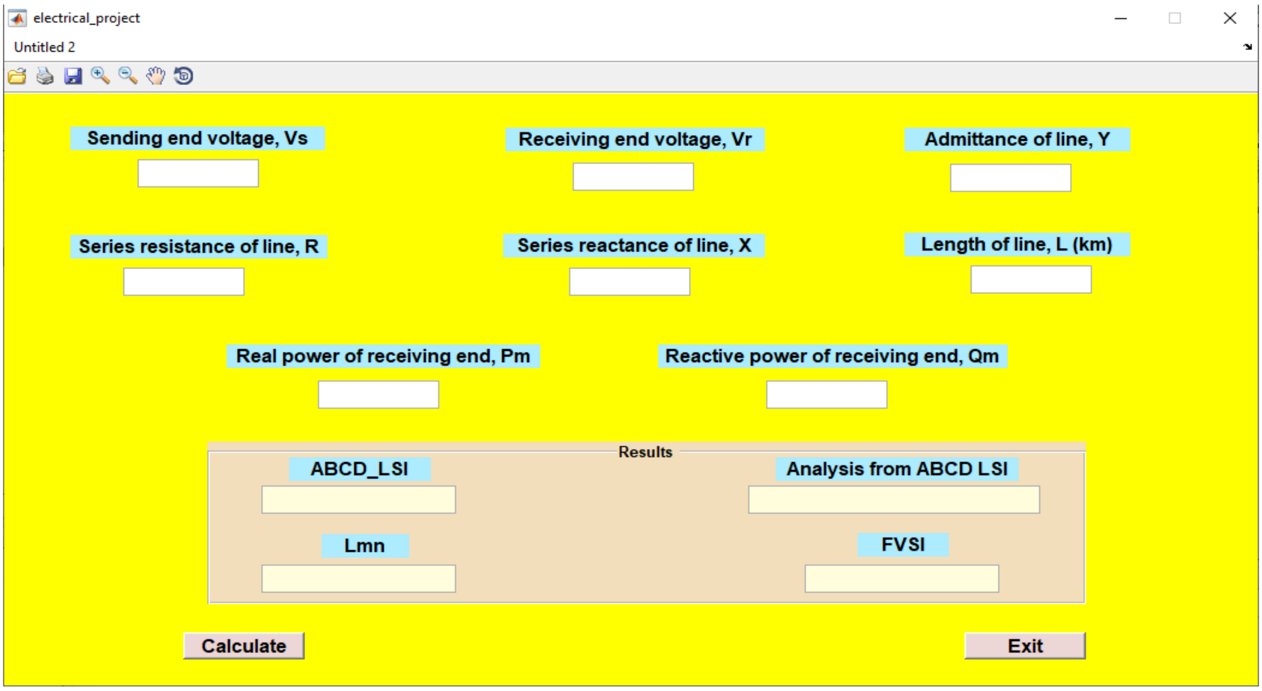


Fig 8: Graphical user interface for the test the stability of the three indices: Lmn, FVSI andABCD_LSI

DISCUSSION

The developed index ABCD_LSI, takes into account the admittance and the length of the transmission line while the Lmn and FVSI are independent of the admittance and length of the line. Therefore, it has an advantage of simplicity, the parameters are easy to work with, and it caters for all types of transmission line: short, medium and long line. The developed stability indexin this research was simulated and compared to the Lmn and FVSI indices on the IEEE 5-bus system for its validation.

Discussion of the simulation results for the IEEE 5-bus test system

For the base case, simulation results for the IEEE 5-bus test system shows that the system is stablebecause the values of the three indices are approximately equal and below one (< 1). Bus 5 has been shown to be the weakest bus in the contingency case, as the values of the indices are very similar to one (~1). It means the proximity to failure of the voltage and it has the smallest0.92MVAr reactive total allowable charge. This means that bus 5 is the ideal position for putting a potential compensating system to increase the pressure profile in the bus as a precaution againstthe collapse of the voltage. The voltage at which the bus is on the maximum allowable load is referred to as the critical voltage for bus 3 is 1.0 p.u.

CONCLUSION

A specific stability index (ABCD_LSI) for the prediction of voltage failure in power system networks has been proposed and built in this research work. It is a useful tool for defining the weakest bus, the most important line for a specific load bus in the power system network. This will help to determine the load shedding area and also the maximum load strength of the load buses. This will then instruct the operator to take immediate action to prevent the collapse of voltage when a specific bus is overloaded and where compensation devices are so revealed to be mounted.

Contribution to Knowledge

The contributions of this project are summarized below:

1. A new line voltage stability index suitable for the prediction of voltage collapse of power system networks was developed in this research and this contribute to the present body of knowledge in voltage stability study.
2. Successfully developed and implemented a related software system (based on this index) for simulating and implementing voltage stability indices in the MATLAB

context.This will provide researchers in the study domain with a toolkit.

3. The development in its present form stability index can be applied to any stability analysis and voltage collapse prediction power system in Nigeria.

Future Work

1. Incorporating modeling and analysis of compensating devices such as generators and compensating devices using the developed line stability index to improve voltage stabilityof power system networks can be a good extension of the work reported in this final yearresearch.
2. It is important to take into account the length of the line and the admittance for the calculation of line stability index, which makes the indices more accurate and valid.

REFERENCES

[1] I. A. Samuel, J. Katende, C. O. A. Awosope, and A. A. Awelewa, "Prediction of Voltage Collapse in Electrical Power System Networks using a New Voltage Stability Index," vol. 12, no.2, p. 11, 2017.

[2] L. Zheng, W. Hu, Y. Min, and J. Ma, "A Novel Method to Monitor and Predict Voltage Collapse: The Critical Transitions Approach," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1184–1194, Mar. 2018.

[3] I. G. Adebayo, A. A. Jimoh, and A. A. Yusuff, "A comparison of voltage collapse point prediction capabilities of voltage stability index and inherent structural characteristics," in *AFRICON 2015*, Addis Ababa, Ethiopia, 2015, pp. 1–5.

[4] N. Aminudin, T. K. A. Rahman, N. M. M. Razali, M. Marsadek, N. M. Ramli, and M. I. Yassin, "Voltage collapse risk index prediction for real time system's security monitoring," in *2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)*, Rome, Italy, 2015, pp. 415–420.

[5] P. Mohammadi, A. Shamim, H. Lesani, J. Erfanian, and Y. Mohammadiosmanvandi, "A new approach to voltage collapse point assessment by continuous Tellegen's power flow," in *2015Modern Electric Power Systems (MEPS)*, Wroclaw, Poland, 2015, pp. 1–5.

[6] C. Sharma and M. G. Ganness, "Determination of the applicability of using modal analysis for the prediction of voltage stability," in *2008 IEEE/PES Transmission and Distribution Conference and Exposition*, Chicago, IL, USA, 2008, pp. 1–7.

[7] Y. Xu *et al.*, "Assessing Short-Term Voltage Stability of Electric Power Systems by a Hierarchical Intelligent System," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 27, no. 8, pp. 1686–1696, Aug. 2016.

[8] C. Zheng, V. Malbasa, and M. Kezunovic, "Regression tree for stability margin predictionusing synchrophasor measurements," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1978–1987, May 2013.

[9] H. Lorenzen, J. Timmerberg, and S. Mylvaganam, "Risk assessment of stability loss: Experimental investigations of weak bus bars," in *2016 12th IEEE International Symposium on Electronics and Telecommunications (ISETC)*, Timisoara, Romania, 2016, pp. 281–284.

[10] Y. Lee, Y. Zhao, S.-J. Kim, and J. Li, "Predicting voltage stability margin via learning stability region boundary," in *2017 IEEE 7th International Workshop on Computational Advancesin Multi-Sensor Adaptive Processing (CAMSAP)*, Curacao, 2017, pp. 1–5.

[11] I. Musirin, T. Khawa, and A. Rahman, "Simulation technique for voltage collapse prediction and contingency ranking in power system," in *Student Conference on Research and Development*, Shah Alam, Malaysia, 2002, pp. 188–191.

[12] M. Usama, H. K. Mohamed, I. A. M. El-Maddah, and M. A. Shedied, "A smart voltage stability maneuver Algorithm for voltage collapses mitigation," p. 7.

[13] F. Xue, Z. Chen, and H. F. Wang, "A Novel Criterion for Online Prediction of Voltage Collapse," in *Proceedings of the 41st International Universities Power Engineering Conference*, Newcastle upon Tyne, UK, 2006, pp. 416–420.

[14] V. Balamourougan, T. S. Sidhu, and M. S. Sachdev, "Technique for online prediction of voltage collapse," *IEE Proc. - Gener. Transm. Distrib.*, vol. 151, no. 4, p. 453, 2004.

[15] A. Chandra, A. K. Pradhan, and A. K. Sinha, "A comparative study of voltage stability indices used for power system operation," in *2016 21st Century Energy Needs - Materials, Systemsand Applications (ICTFCEN)*, Kharagpur, India, 2016, pp. 1–4.

[16] M. Donolo, M. Venkatasubramanian, A. Guzman, and F. de Villiers, "Monitoring and mitigating the voltage collapse problem in the Natal network," in *2009 IEEE/PES Power SystemsConference and Exposition*, Seattle, WA, USA, 2009, pp. 1–5.

[17] M. A. Mostafa, "Application of regression analysis for predication of voltage collapse in power systems," in *2008 12th International Middle-East Power System Conference*, Aswan, Egypt, 2008, pp. 529–535.

[18] M. Nizam, A. Mohamed, and A. Hussain, "Dynamic Voltage Collapse Prediction In Power Systems Using Power Transfer Stability Index," in *2006 IEEE International Power and Energy Conference*, Putra Jaya, Malaysia, 2006, pp. 246–250.

[19] D. Idoniboyeobu, S. L. Braide, and A. O. Idachaba, "Analysis of Voltage Collapse in the Nigeria 30 Bus 330kv Power Network," p. 9.

[20] N. R. Beeravolu, I. Leevongwat, and P. Rastgoufard, "Predicting voltage abnormality using power systems dynamic response," in *2014 Clemson University Power Systems Conference*, Clemson, SC, USA, 2014, pp. 1–7.

[21] M. Khalilifar, M. Joorabian, S. Gh. Seifosadat, and S. M. Shahrtash, "Estimation of time to voltage collapse," in *2016 IEEE 16th International Conference on Environment and ElectricalEngineering (EEEIC)*, Florence, Italy, 2016, pp. 1–6.

[22] T. Paul, H. Ravindra, M. Steurer, and J. W. Kimball, "Voltage stability preserving invariants for smart grids," in *2015 IEEE Power and Energy Conference at Illinois (PECI)*, Champaign, IL, USA, 2015, pp. 1–6.

[23] T. A. Evers, C. L. Pierre, G. L. Lebby, and Y. D. Song, "Prediction of voltage collapse in power systems," in *Proceedings of Thirtieth Southeastern Symposium on System Theory*, Morgantown, WV, USA, 1998, pp. 354–358.

[24] H. Nouri, T. S. Davies, and R. A. Mukhedkar, "Prediction of network voltage collapse through simulatiosn," in *2000 10th Mediterranean Electrotechnical Conference. Information Technology and Electrotechnology for the Mediterranean Countries. Proceedings. MeleCon 2000(Cat. No.00CH37099)*, Lemesos, Cyprus, 1998, vol. 3, pp. 1080–1083.

[25] L.-A. Dessaint, I. Kamwa, and T. Zabaiou, "Preventive control approach for voltage stability improvement using voltage stability constrained optimal power flow based on static line voltage stability indices," *IET Gener. Transm. Distrib.*, vol. 8, no. 5, pp. 924–934, May 2014.