IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 13, Issue 4 Ver. III (Jul. – Aug. 2018), PP 42-50
www.iosrjournals.org

Analysis of Voltage Collapse in the Nigeria 30 Bus 330kv Power Network

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Abstract: *In this paper, a novel approach to voltage collapse analysis using a probabilistic predictor-detector that relies on a conditioned probabilistic Quadratic Line Voltage Stability Index coined the q-LVSI and a moving average filter coined pq-LVSI for deductive analysis of power system network state. The proposed technique uses simple rules for logical analysis such as ratio-sum-of-thresholds, mean-value analysis and confidence conditioning to detect and estimate the presence of a collapsing signal from a sequence of several q-LVSI estimates and for several simulation runs. A moving average filter consisting of long-term and short-term predictions is used to filter and enhance the predictions from the resulting q-LVSI values prior to probabilistic logical analysis. The technique is applied to some interconnected buses of the Nigeria power system network in order to determine the interconnected bus sequence(s) that are most likely to collapse. Simulations are performed in the MATLAB language and the results indicate that the Shiroro-Kaduna bus sequence has a higher tendency to collapse earlier when compared to the others. The results also show that the moving average filter long predictions will timely predict the interconnected power system line with the most likelihood of a collapse when there is a differential in the lead and lag parameters.*

Keywords: *LVSI, Moving-Average, Power System, Voltage Collapse, Transmission line*

Date of Submission: 22-08-2018 Date of acceptance: 08-09-2018

I. Introduction

In Nigeria, the evolution of more power hungry devices followed with exponential urban growth has resulted in abysmally low voltages leading in turn to unwarranted blackouts experienced by the citizenry. Power system experts have described the prevailing outages as "Voltage Collapse", a phenomenon that has been widely studied by many power system researchers around the world. Voltage collapse can hamper power system operations by denying the consumers constant and reliable source of electricity. The Voltage Stability Index (VSI) defines a measure and margin of safety for determining the possibility of bus voltage collapse in an interconnected power system network. It has been employed by power system researchers to evaluate line voltage collapse indices. Using the VSI, it has been shown experimentally that the Nigerian power network will exhibit a tendency to experience voltage collapse at some buses during reactive power loading. Thus, there is an urgent need to deploy preventative approaches in such power system networks in order to avert possible downtimes and secure the electrical power system. In this paper, we propose an approach called the Predictive Line Voltage Stability Index (p-LVSI) that will enable timely determination of voltage collapse regions in the Nigerian 330kV 30-bus power system transmission network. We show that with this approach, it is possible to classify the regions that are more or less probably unstable probabilistically.

II. Related Works

Research in studying the problem of voltage collapse is an active area of research that has led to the development of several VSI metrics. In Wang et al (2009) an equivalent node voltage collapse index (ENVCI) based on an equivalent system model and requiring only the voltage phasor information from local network for real-time and online power applications was proposed. ENVCI was used for determining the weakest bus and the system voltage collapse point.

In Tiwari et al (2012), a line collapse proximity index (LCPI) incorporating the effects of the relative direction of real/reactive power flows, using the ABCD parameters of the transmission network and based on exact transmission system model was proposed. The index ranges are typically between 0 and 1 with values close to 0 indicating a collapsing bus or power node. The system was applied to the IEEE 30 and IEEE 118 bus system with promising comparative results with other existing stability indices.

In (Peter & Sajith, 2014), Artificial Neural Networks (ANNs) have been used in conjunction with the power line stability index (L-index) to predict an imminent voltage collapse point. The L-index has been proposed earlier in (Tiwari et al, 2012). The MATLAB Power System Analysis Toolbox (PSAT) was used for load flow analysis and MATLAB neural network toolbox for the neural network prediction analysis.

In (Pérez-Londoño, et al, 2014), a simple and less computational expensive voltage stability Index to measure the proximity of voltage collapse point is proposed; this index is based on the concept of relative electrical distance and also assume the availability and use of voltage phasor measurement unit (PMU).

An approximate voltage stability index, the Voltage Margin Index (VMI) based on Local Impedance Matching (LMI) technique was proposed in (Toban V et al, 2014). The technique proferred a cheaper alternative index by avoiding the computation of PQ and PV curves.

In Aldeen et al (2015) linear time invariant-like voltage gain and phase margins akin to that used in control systems were proposed for the development of Voltage Stability Margins (VSM) for risk assessment in smart power grids.

In Moger & Dhadbanjan (2015), reactive power loss index (RPLI) which is a non-iterative voltage stability index was proposed for the identification of weak buses and optimal placement of reactive power compensation devices. Their proposed approach was tested on a sample 10-bus and practical 72-bus (Indian) power system. Their proposed approach was able to show close agreement with other conventional (iterative) techniques such as the V-Q Sensitivity Modal Analysis due to Gao et al (1992) and the Continuous Power Flow (CPF) technique due to Ajjarapu & Christy (1992).

In Sanz et al (2015), voltage collapse proximity estimation based on a vulnerability strategy have been proposed. A voltage collapse proximity index was established from voltage profile databases derived from a variety of contingencies.

Chuang et al (2016) developed the Integrated Transmission Line Transfer Index (ITLTI) for voltage stability margin (VSM) computation and weak bus identification. The proposed index was studied under reactive power loading on the IEEE 14-bus power network and gave reasonable error comparisons with some existing techniques indicating a close VSM agreement.

In (Nascimento & Gouvea Jr , 2017) Flexible AC Transmission (FACTS) devices and evolutionary algorithm has been used to optimally adjust the voltage collapse margin and other associated power system parameters.

The use of Multi Agent System (MAS) for voltage control with voltage trend prediction has been proposed in Nassaj & Shartash (2018); MAS is an Artificial Intelligence (AI) technique used to solve complex problem via sub-problem decomposition and agent delegation management operations. This technique has been used specifically in (Islam et al, 2014) for voltage collapse prevention in a receding horizon control (RHC) MAS scheme.

In Hashemi et al (2018), a demand response (DR) approach to voltage security margin based on two-state algorithm was utilized in conjunction with a swarm intelligence optimization algorithm called Particle Swarm Optimization (PSO) used in turn for finding optimal load reduction pattern and tested on IEEE 39-bus power network. The DR technique allows for a participatory load shedding scheme by end-users of electrical power. The authors used a Load Impedance-Thevenin reactance ratio as stability index for evaluation purposes.

In (Vahid-Pakdel et al, 2018), the impact of Natural Gas supply on the Voltage Stability Margin (VSM) was investigated upon in the context of multicarrier systems as an alternative curtailment strategy with the goal of cutting down cost of the conventional load curtailment strategy.

Further details on the Voltage collapse mechanism, Voltage Stability Indices (VSI), classifications and related issues can be found in the review by Modarresi et al (2016).

III. Methodology

In this section, we present a new approach based on a metric called the Quadratic Line Voltage Stability Index (q-LVSI) proposed in (Ratra et al., 2018). The power system used for the analysis is as shown in Fig1. The metric used considers the line impedance and charging capacitances including bus voltage and angle parameters of the network. Thus, it is a more complete model than those proposed earlier such as the Line Stability Index (LSI) proposed in (Moghavvemi & Omar, 1998), Line Stability Factor (LQP) proposed in (Mohamed & Jasmon, 1995) and Fast Voltage Stability Index (FVSI) in Musirin & TKA (2002).

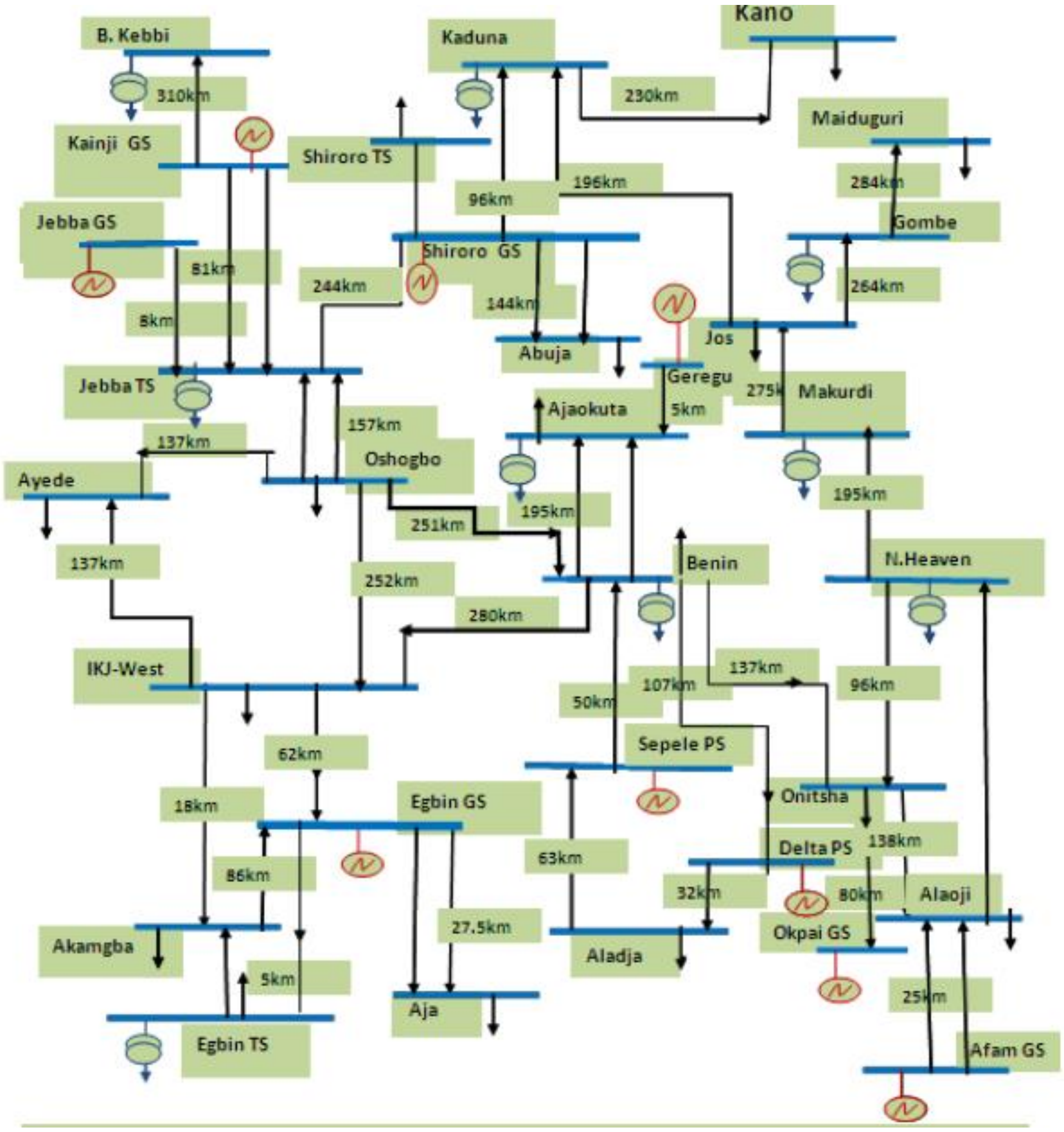

Fig.1: The Nigerian 330kV 30-bus network; Source: Ogbuefi & Madueme (2015)

The Newton Raphson (NR) load flow analysis (LFA) is as shown in the flow diagram of Fig 2. In this figure, the system bus parameters such as line impedances, bus generation real and reactive (complex) powers, initial bus voltage/angle guesses and the NR parameters such as the number of simulation runs and stopping criterion are all specified. The simulation is performed for the stipulated number of trial runs (following convention) and then the actual bus voltage, angles and line flows are computed and stored once the simulation completes.

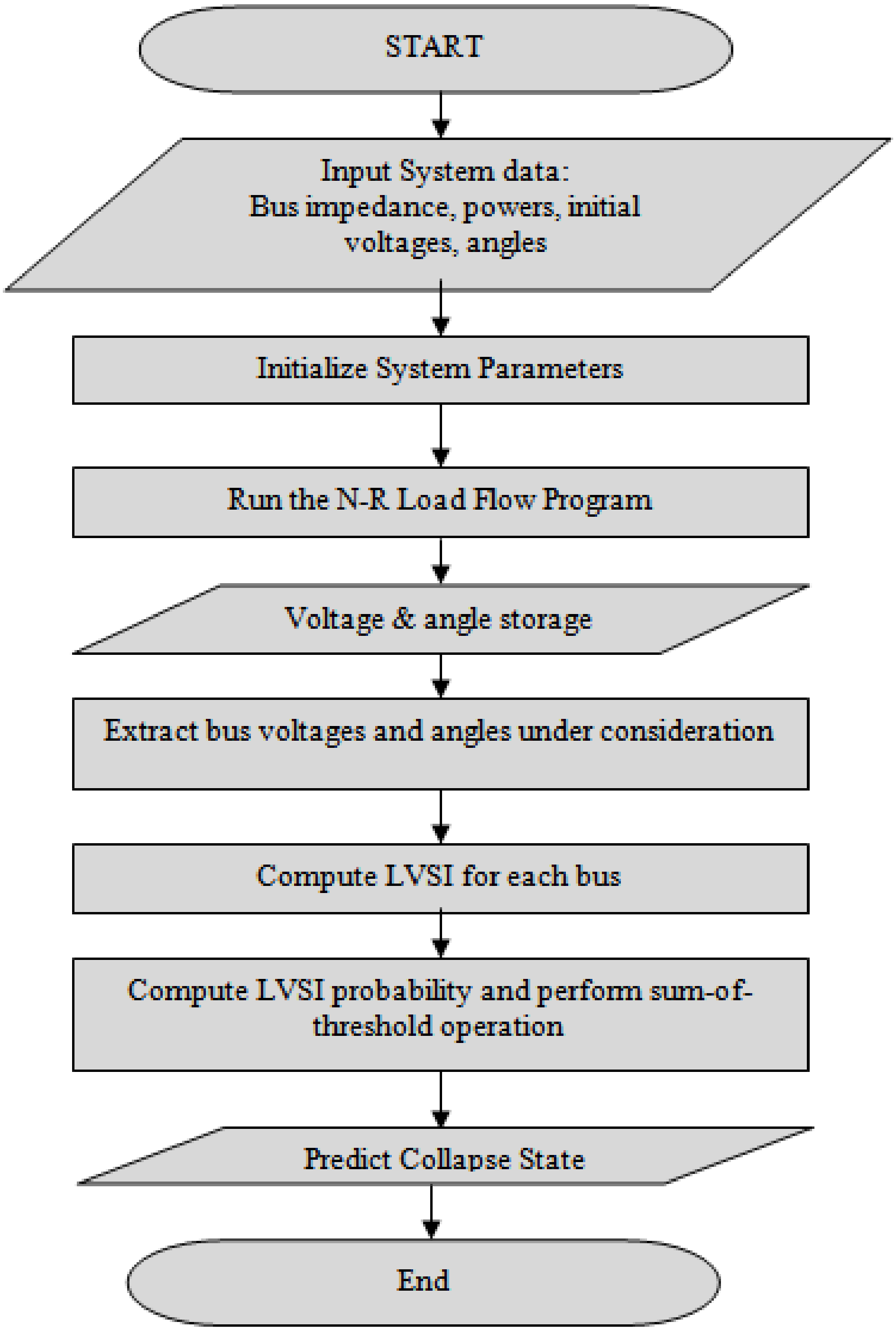

Fig.2: Flow Diagram for LVSI Calculation/Prediction Scheme
(Source: Ratra et al., 2018).

We use The Quadratic Line Voltage Stability Index (q-LVSI) as a Voltage Collapse Metric (VCM) which uses the ABCD transmission line parameters for computing the voltage stability margins of a power system network (Ratra et al., 2018). It is called quadratic here since it was derived from a voltage quadratic equation; q-LVSI avoids the confusion with the LVSI earlier proposed in (Sungayadevi, 2009).
In order to compute the q-LVSI, we the steps as follows:
[Step].1 Define the required bus voltages (sending and receiving end voltages) and the corresponding phase angles; also define the transmission line parameter including the ABCD model descriptors for the considered lines.

[Step].2 Model a phase angle δ_{SRj} as a difference between a sending and receiving end voltage of a given line.

[Step].3 Model the receiving end active power in terms of the ABCD parameters as:

a. $$P_R = \frac{V_S V_R \cos(\beta - \delta)}{B} - \frac{A V_R^2 \cos(\beta - \alpha)}{B} \quad (1)$$

[Step].4 Form a quadratic equation from eqn(3.2) in Step 3 above by simplification/cross-multiplication and shifting all terms to the left as:

a. $$V_R^2 - \frac{V_S V_R \cos(\beta - \delta)}{A\cos(\beta - \alpha)} - \frac{P_R B}{A\cos(\beta - \alpha)} \quad (2)$$

[Step].5 Compute the sensitivity of V_R as a differential change in V_R with respect to received power, P_R as:

a. $$\frac{\partial V_R}{\partial P_R} - \frac{-B}{2V_R A\cos(\beta - \alpha) - V_S \cos(\beta - \delta)} \quad (3)$$

[Step].6 Define a voltage stability requirement as:

a. $$\frac{-B}{2V_R A\cos(\beta - \alpha) - V_S \cos(\beta - \delta)} < 0 \quad (4)$$

from which we obtain:

b. $$V_S \cos(\beta - \delta) - 2V_R A\cos(\beta - \alpha) < 0 \quad (4)$$

[Step].7 Using eqn(3.6b), define a voltage collapse avoidance satisfiability criteria as:

a. $$\frac{2V_R A\cos(\beta - \alpha)}{V_S \cos(\beta - \delta)} > 1 \quad (5)$$

The LVSI is thus computed as:

$$LVSI = \frac{2V_{Rj} A_j \cos(\beta_j - \alpha_j)}{V_{Sj} \cos(\beta_j - \delta_{SRj})} \qquad \forall\, j = 1, 2, 3, \cdots, l \quad (6)$$

where,

V_{Rj} = receiving voltage at bus at line j

V_{Sj} = sending voltage at bus at line j

A_j = a transmission line parameter

α_j = the angle part of transmission line parameter A at line j

β_j = the angle part of transmission line parameter B at line j

δ_{SRj} = Phase angle difference between sending and receiving end voltages at line j

l = nth line

In order to describe a probabilistic explanation for the voltage collapse point, we define and compute two new variables namely:

- LVSI probability
- degree of Confidence estimate

LVSI probability

The LVSI probability is actually an energy model defined as a ratio of an iterated LVSI summation process to the number of trial runs to maximize a voltage expectation defined as a sequence of normalized probabilities. It is expressed as shown in eqn. (7).

$$p_{LVSI(k)} = \frac{\sum_{k,j} LVSI \geq l_{TH}}{n_{trial}} \quad (7)$$

The threshold l_{TH} is described by the mean value of the LVSI of all buses for different trials as:

$$l_{TH} = \frac{\sum_{i=1}^{ntrials} LVSI_{k=1}^{l}}{n_{trials}} \quad (8)$$

Since the *LVSI* is described by a threshold parameter, l_{TH} , as in eqn. (8), there is a sparse connectivity rule that applies to assure a probabilistic interpretation of voltage indices; energy is assumed to be gained if p_{LVSI} is 1 otherwise it is lost – see eqn. (7). The lower the p_{LVSI} estimate, the greater the entropy in the probabilistic energy model of eqn. (7)

degree of Confidence estimate

Based on a degree of confidence criterion (doC), a collapse prediction may be inferred for a given set of trial bus loading; if the doC is below a pre-specified threshold, then we may accept the fact that a voltage collapse is imminent; otherwise the line voltage is relatively stable – see eqn.(9).

$$V_{collapse} = \begin{cases} p_{LVSI(k)} < d_o C, & accept \\ otherwise, & reject \end{cases} \quad (9)$$

The presence of a collapsing signal is indicated by a value of 0 otherwise its value is equal to 1.

IV. Experimental Details And Results

Simulations have been performed in the MATLAB language and using Nigerian 30 bus 330kV power system transmission line data available from the National Control Centre (NCC) Osogbo, Nigeria.

Simulation Task

The task is to vary the chosen load bus voltages in such a way and manner as to emulate a real world stochastic voltage drop process that follows a known Gaussian of zero mean and unit variance; then using the LSVI as a detector-predictor (LVSI-DEP) identify the buses with a high likelihood of a collapsing state. The computed bus voltage values are first solved using the Newton-Raphson technique then the required bus voltages/angles are read out and recorded as well as their corresponding line parameters. The generated (solved) voltages/angles for the buses considered at the first trial (at zero loading) are as shown in Table 1; the associated line parameters are obtained from the NCC Osogbo, Nigeria.

Table 1: Voltage and Phase Angles for Considered Lines

Bus no.	Bus Name	Voltage (p.u)	Angle (rad)	Description
1	Egbin-GS	1.0000	0.0000	Gen bus
5	AFAM-GS	1.0000	0.3043	Gen bus
8	SHIRORO-PS	1.0000	-0.5057	Gen bus
12	IKEJA-WEST	0.9930	-0.0961	Load bus
26	ALAOJI	0.9564	0.2707	Load bus
29	KADUNA	0.8738	-0.6941	Load bus

The results of using the Quadratic Line Voltage Stability Index (q-LVSI) technique is presented in this section using the methods described in the previous chapter. The values presented in Table 1 serve as input to the q-LVSI model formula, which generates (computes) the stability indices. These stability indices serve as input to a MATLAB moving average filter function for further analysis.

Results of the Line Voltage Stability Index simulation

The response of the q-LVSI predictive technique proposed for bus line sequence b1-b12, b5-b26, and b8-b29 is presented by the bar plot in Fig 3. The response graph shows the computed index for each bus at different percentage loading reactive power using the Newton-Raphson (N-R) technique. The results indicate that the Bus 3 exhibits a tendency to move towards the collapse threshold than Bus 1 and 2. The simulations are made using a collapsing threshold; l_{TH} equal to 1.5 which is the median value i.e. the middle value of the q-LVSI boundary typically between 1 and 2.

Using a moving average filter, the trend response is as shown in Figures 4 and 5 for the short and long versions respectively; the lead, lag and alpha parameters of the moving average filter are all set to 1.

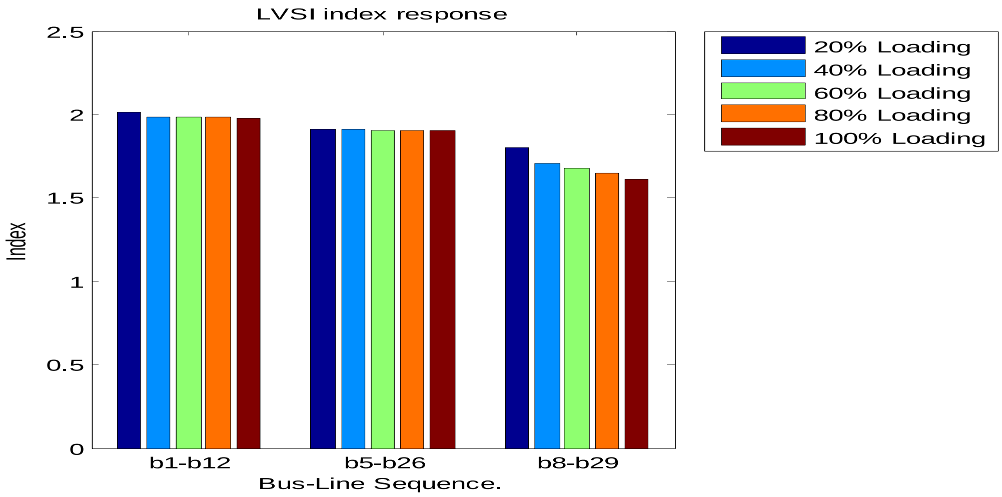

Fig 3: q-LVSI response for bus line sequence b1-b12, b5-b26, and b8-b29

Comparative Prediction Results of the LVSI with moving average filter predictor

A comparative report showing the performance of the q-LVSI with a moving average filter incorporated is presented. The q-LVSI generated values are fed The voltage collapse prediction results of bus line sequence b1-b12, b5-b26, and b8-b29 using the proposed predictive q-LVSI (q-LVSI) and the generated moving average short/long (pq-$LVSI_{short}$, pq-$LVSI_{long}$) predictions are as shown in Table 3.

Table 2: Voltage collapse prediction for considered lines at lead=2, lag=3, alpha=1

Line Sequence	q-LVSI	pq-$LVSI_{short}$	pq-$LVSI_{long}$
b1-b12	1	1	1
b5-b26	1	1	1
b8-b29	1	1	0

The simulations are made using a threshold, l_{TH} equal to1.5 and a confidence limit, $d_o C$, equal 0.7. The parameters of the moving average filter are 2, 3 and 1 for the lead, lag and alpha respectively. The results indicate that the q-LVSI and pq-LVSI moving average short are unable to predict an imminent voltage collapse; however, the pq-LVSI moving average long will predict a voltage collapse for line sequence b8-b29.

Furthermore, it was noted that by making the lead parameter and lag parameter equal to 3, both the pq-LVSI moving average short and the pq-LVSI moving average short predicted a voltage collapse for line sequence b8-b29 (see Table 3).

Figure 4 and 5 shows the line voltage index bar plot of bus line sequence b1-b12, b5-b26, and b8-b29 respectively for the proposed moving average short/long (pq-$LVSI_{short}$, pq-$LVSI_{long}$) predictions and based on the results and parameter settings as indicated in Table 1. The response shows a reducing LVSI which is more pronounced at the 20% loading level; this indicates that the moving average filters are trying to predict the outcome of the q-LVSI generated values.

Table 3: Voltage collapse prediction for considered lines at lead=3, lag=3, alpha=1

Line Sequence	q-LVSI	pq-$LVSI_{short}$	pq-$LVSI_{long}$
b1-b12	1	1	1
b5-b26	1	1	1
b8-b29	1	0	0

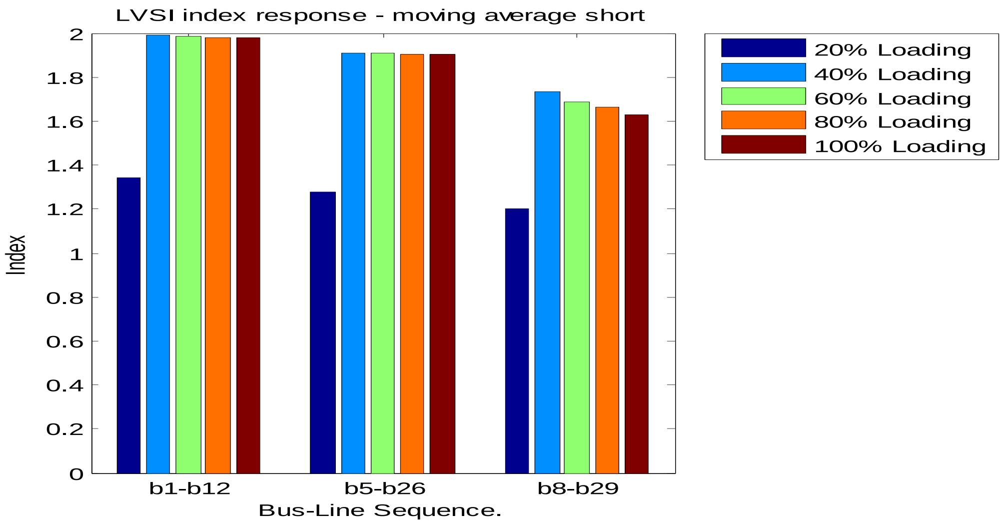

Fig 4: pq-LVSI response for bus line sequence b1-b12, b5-b26, and b8-b29 – Moving Average Short

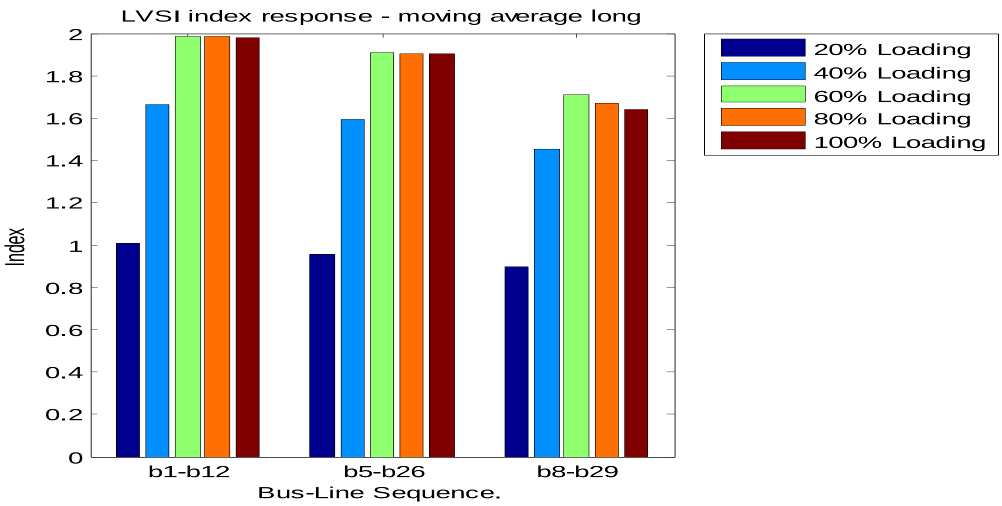

Fig 5: pq-LVSI response for bus line sequence b1-b12, b5-b26, and b8-b29 – Moving Average Long

Remarks

The results of Table 2 using the aforementioned system parameters shows that only the proposed pq-LVSI technique with moving average filter prediction-long will be able to predict voltage collapse when there is a differential in the lead and lag parameters; the q-LVSI and the pq-LVSI with a moving average filter prediction-short will not be able to make a correct prediction with this setting. It is important to note that the setting of the moving average filter parameters is crucial to the quality of its prediction. In particular, the pq-LVSI technique with moving average filter prediction-long is indicative of the true predictive state of a moving average based q-LVSI.

V. Conclusions

This paper has proposed a new approach to analyze the voltage collapse in a typical existing power system. It involved the extension of a quadratic predictive line voltage stability index (Qp-LVSI) model using a probabilistic moving average filter detector-predictor. Using this approach, it is possible to infer the likelihood of a voltage collapse before its occurrence.

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Idoniboyebu D. C " Analysis of Voltage Collapse in the Nigeria 30 Bus 330kv Power Network "IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) 13.4 (2018): 42-50.