Nigerian Journal of Technology (NIJOTECH)
Vol. 38, No. 2, April 2019, pp. **470 – 475**

Print ISSN: 0331-8443, Electronic ISSN: 2467-8821
www.nijotech.com
http://dx.doi.org/10.4314/njt.v38i2.25

ESTIMATING THE MARGIN TO VOLTAGE COLLAPSE IN A DWINDLING ELECTRIC POWER NETWORK

J. N. Onah[1, *], Z. O. O. Jagun[2], T. C. Madueme[3] and S. E. Oti[4]
[1, 3, 4,] DEPARTMENT OF ELECTRICAL ENGINEERING, UNIVERSITY OF NIGERIA, NSUKKA, ENUGU STATE, NIGERIA.
[2,] DEPARTMENT OF COMPUTER & ELECTRICAL ENGINEERING, OLABISI ONABANJO UNIVERSITY, IBOGUN CAMPUS, OGUN STATE. NIGERIA.
E-mail addresses: [1] *jonas.onah.pg.65348@unn.edu.ng*, [2] *jagun.zaid@oouagoiwoye.edu.ng*, [3] *theophilus.madueme@unn.edu.ng*, [4] *stephen.oti@unn.edu.ng*

ABSTRACT
For more than a decade, Nigeria National Grid (NNG) has encountered an average of 24 times per year of total incidences of voltage collapse in the system. Nigerian manufacturers, small scale businesses, families including private households have been unable to break even in their businesses owing to this ugly trend. The main focus of the work is to estimate the limit and margin of active power transmission across a certain defined boundary prio to voltage collapse. This **will help to alert the power systems operators and planners about the dangers that lie ahead in case of any voltage collapse scenario.** ***The paper made an exploit of Continuation Power Flow to determine the Margin to Voltage Collapse (MVC) of NNG. The effectiveness of the approach was tested in the 10Bus NNG and 30Bus NNG. For the 10Bus NNG, the results show that at 15th iteration the corrector solution (4.3698pu) was found to be too far from the predictor value (1.7454pu). However, the maximum loading Parameter 4.3698pu with a mismatch of 0.00324pu converged at 40th iteration search in 1.5016 seconds. To enable quicker convergence of the solutions and the computation speed, the step size was reduced to 0.04. The MVC for the 10Bus NNG and 30Bus NNG are estimated to be 4.1698 p.u and 3.5 p.u respectively.***

Keywords: *CPF, MVC, Voltage Collapse, Voltage Stability, Saddle Node Bifurcation Point, Current Operating Point*

1. INTRODUCTION

One of the cardinal roles a control system Engineer working in a control room of a dwindling electric power system is the restoration of satisfactory services. Moreover, the estimation of the vulnerability to voltage collapse near the saddle node bifurcation point of a power system will help utility engineers in that regard. Owing to the impacts of system disturbances and enormous losses associated with incidences of voltage collapse of the Nigeria National Grid, an accurate approach that will inform the electric power utilities about the Margin to Voltage Collapse is explored. The Nigerian National Grid is run and controlled by Transmission Company of Nigeria (TCN), [1]. Prior to the privatization, it was formally known as National Electric Power Authority (NEPA). Later on, it was sold to Power Holding Company of Nigeria. The control of the grid is affected by eight (8) Regional control centers (RCC) located at Lagos, Oshogbo, Benin, Enugu, Port Harcourt, Bauchi, Kaduna and Shiroro. Shiroro is normally taken as sub-National control center (SNCC). The operations in these regional control centers (RCC) are co-ordinate, directed and supervised by the National control center at Oshogbo. The Grid issues of major concerns includes but not limited to; reactive reserves being exhausted, reactive power demand of load not being met owing to shortage in reactive power production and transmission, incessant outages of generators and transmission lines, generating stations being far from the load centers, voltage drops owing to the real and reactive power flow along the transmission lines, [1]. Moreover, in the present utility practice, operational measures of vulnerability to voltage instability are

* Corresponding author, tel: +234 – 803 – 276 – 2616

typically based on the incessant blackouts observed in the recent times in the Nigerian power system owing to zero or not having enough reactive reserves as noted by Onah *et al* [2]. IEEE/CIGRE, [3] observed that voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. On the other hand, Beena [4] opined that a power system will experience voltage collapse when the loads increase up to a certain critical limit, where the system physically cannot support the amount of connected load. This point is called critical point or a Saddle-Node Bifurcation point (SNBP). It corresponds to a generic instability of parameterized differential equation models. This signifies the intersection point where different branches of equilibrium meet. At this point, the Jacobian matrix of the system is singular and the system loses stability bringing the typical scenario of voltage collapse. However, the ability to maintain voltage stability for the stressed Nigerian National grid is a growing focus for power system planners and operators. Voltage stability studies have relationships with finding the nearness of the power system to voltage instability cum voltage collapse. Figure 1 shows that for more than a decade, voltage collapses of NNG in the form of partial and total collapse have become a recurrent decimal [5]. It has intermittent occurrences of 265 times from the year 2008 to September 2018 which amounts to an average of 24 times per year. It has been reported that Nigeria lost 100billion dollars to voltage collapse by the Transmission Company of Nigeria [6]. Nigerian manufacturers, small scale businesses and families spend on average of 3.5 trillion naira per year to power their generating sets with diesel and petrol due to unstable supply of electricity occasioned by voltage collapse according to report accredited to TCN [6]. Among private households, the Figure is 1.56 trillion naira which is equivalent of 13.35million dollars.

2. APPROACHES TO VOLTAGE STABILITY

Many voltage stability margins and indices have been proposed by some power system researchers and used throughout the world for voltage security analysis. An aspect of voltage stability indices is based on Eigen-value and singular value analysis of the system Jacobian matrix. This aspect relies in predicting the collapse point by monitoring the minimum Eigen-value or singular value of the system Jacobian, which becomes zero at the collapse point [7]. An attempt to review the voltage collapse incidences on Nigerian 330 kV network was made by Samuel, *et al* [8]. The network was modeled using power system simulator software for Engineers (PSS/E). However, the load flow approach exploited in the work cannot evaluate the power system Jacobian at SNBP. To overcome the former, an exploit of voltage collapse margin (VCM) calculation technique using sensitivity method and Singular Value Decomposition on the National grid company (NGC) United Kingdom was made by Ekwue, *et al*, [9].

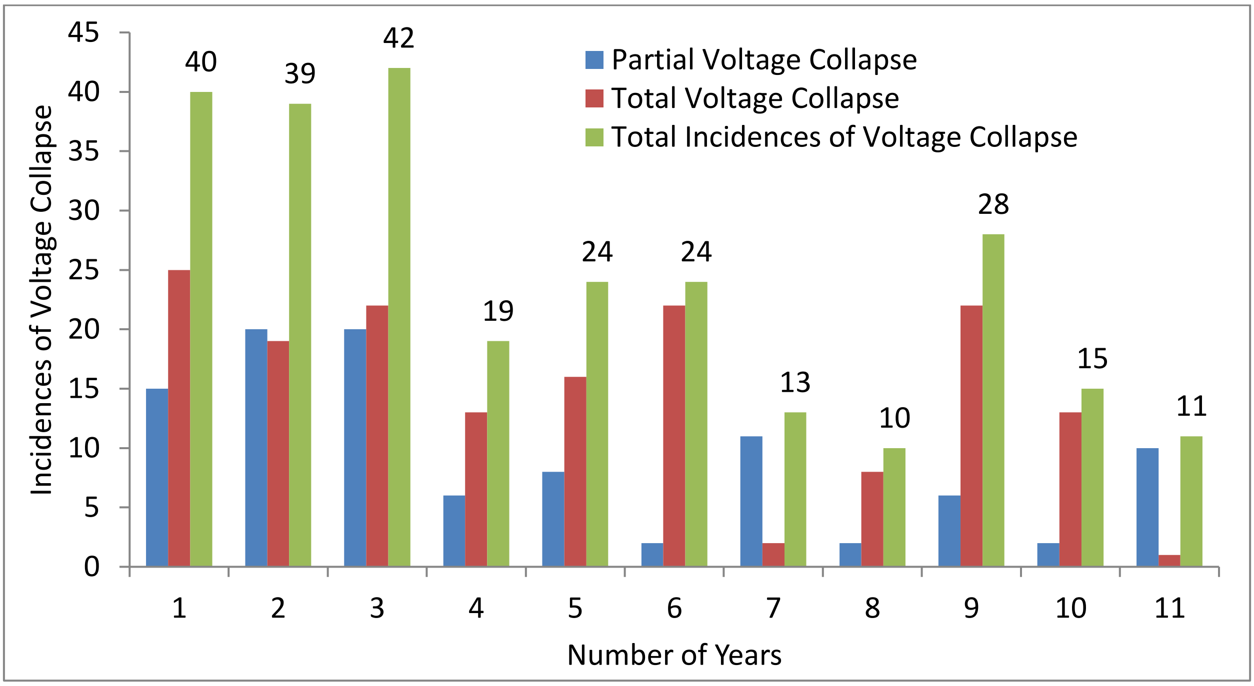

Figure 1: Incidences of Voltage Collapse from 2008 to 2018

The results were found promising but the complexities of the approaches are less accurate in the determination of proximity to voltage collapse at Saddle Node Bifurcation Point (SNBP). VCM plays the role of determining the limit of active power transmission across defined boundaries before voltage collapse would occur. However, the weakness of the bus voltages was determined using singular value decomposition technique. Nwohu, *et al*, [10] used load flow approach for estimating bifurcation point in IEEE 14-bus networks. He assumed that generators would violate their Q-limits before the bifurcation point is reached. But, load flow Jacobian becomes singular at saddle node bifurcation point (SNBP) of a power system. Hence, the approach could not predict voltage collapse at SNBP. Again, it is a well-known fact that bifurcation theory assumes slowly varying parameters. It does not account for the large disturbances that are common among many voltage collapses. In [11-12], Modal Based Analysis was used in the evaluation of voltage stability of IEEE 30 bus network. The determination of the factors that causes voltage instability is a plus. But the concepts of positivity and negativity of Eigen values are less accurate in the prediction of voltage collapse point at SNBP. The difference between the maximum reactive load and the corresponding base case value-for a given set of load buses of a power system was proposed by Van Cutsem [13]. The margin was aimed at assessing the system robustness with respect to voltage collapse. The corresponding collapse point was directly obtained when the solution of an optimization problem with the load increase as the objective function. The non-optimized loads were taken as equality constraints, and the generator reactive limits were seen as inequality constraints. The voltage problems were solved using the Newton's approach. Unfortunately, the method faces convergence problems at SNBP. However, to get across these difficulties, an approach capable of determining the Current Operating Point (COP), Saddle Node Bifurcation Point (SNBP), and Margin to Voltage Collapse (MVC) is explored using predictor, corrector and parameterization schemes of Continuation Power Flow approach.

3. MATERIALS AND METHOD

The data used in the simulation were collated from National Control Center Oshogbo. The MATLAB/SIMULINK Power System Analysis ToolBoX (PSAT) program is used as the simulation software. The one line diagrams of 10-Bus and 30-Bus NNG drawn by PSAT are shown in Figures 2 and 3 respectively. Figure 2 consists of four generators and six load buses. Out of the ten buses, the Ajaokuta load bus is the only bus from the Northern Part of Nigeria in the Figure 2. Meanwhile, the rest of the buses are from the Southern Part of the country. During the simulation, Okpai PV bus was chosen as the reference bus as shown in Figure 2.

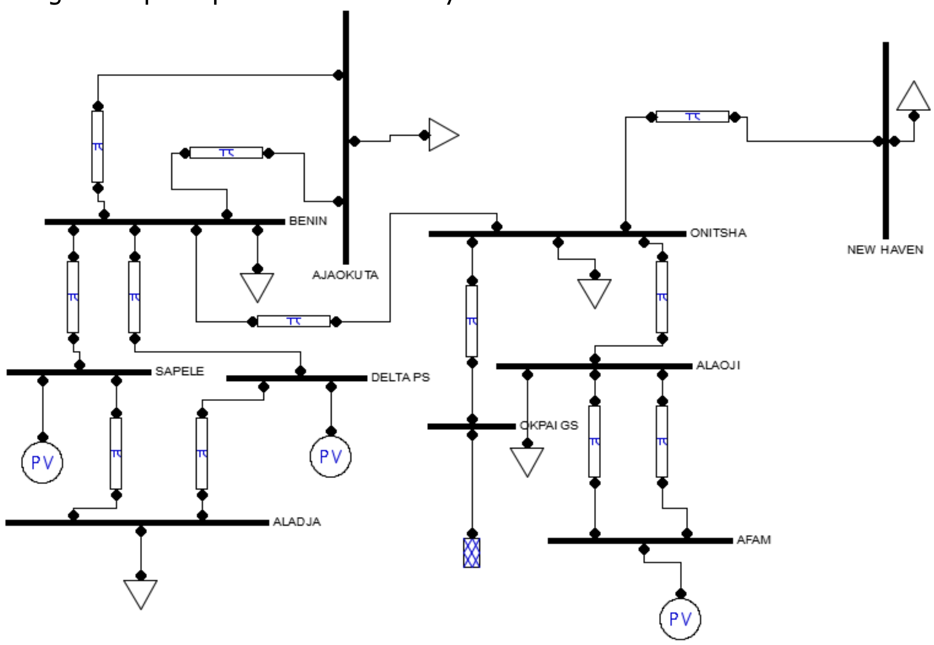

Figure 2: One Line Diagram of 10 bus of Nigeria National Grid (NNG)

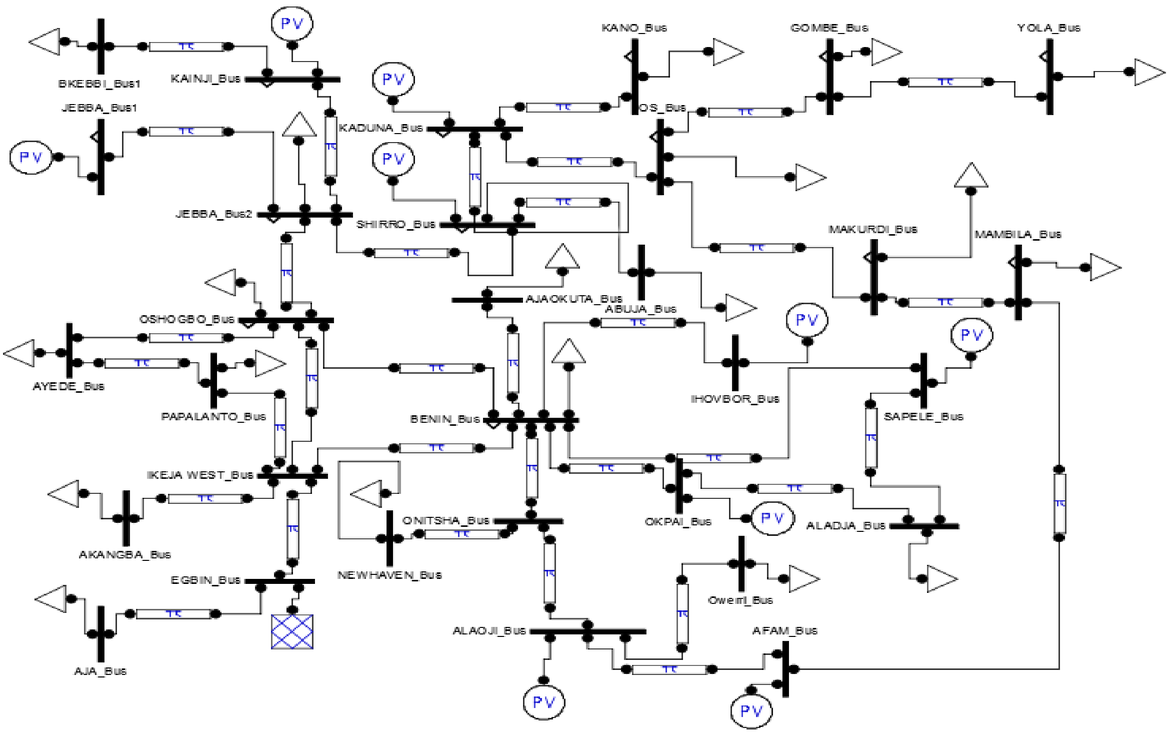

Figure 3: One Line Diagram of 30 bus of Nigeria National Grid (NNG)

3.1 Continuation Power Flow

Exploiting the conventional N-R to solve load flow equation may lead to convergence difficulty around the knee point of the PV Curve. To get across the ditch, an exploit of Continuation Power Flow (CPF) is explored. CPF traces power flow solutions along the P-V curve, the power flow solution at and beyond the equilibrium point. The introduction of a load parameter in the traditional power equations allows load and MW to increase. Supposing the Load Flow is kept constant, the load and generation can be expressed as:

$$P_{li}(\tau) = P_{l0}(1 + \lambda K_{li}) \quad (1)$$

$$Q_{li}(\tau) = P_{l0}(1 + \lambda K_{li}) \quad (2)$$

$$P_{Gi}(\tau) = P_{G0}(1 + \lambda K_{Gi}) \quad (3)$$

Where K_{li} stands for the rate of load change at bus i as λ changes, K_{Gi} stands for the rate of MW change at the generator i as τ changes, P_{li}, Q_{li}, P_{Gi}, are the real, reactive load and real power generation at the bus i respectively. The P_{l0}, Q_{l0}, P_{G0}, are the initial real, reactive load and real power generation respectively. The reformulated power flow equations are:

$$Z(\varphi, \Delta, \lambda) = 0 \quad (4)$$

The continuation parameters such as φ, Δ, λ are the phase angle, the voltage and the loading parameter respectively. It should be noted that the selection of appropriate continuation parameters is very crucial to the convergence of solutions. The state variable with the largest tangent component is first selected as loading parameter. Subsequently, Voltage and phase angle are chosen for a better convergence of solutions.

The whole calculation process includes a series of predictors and correctors. A predictor is a linear extrapolation at the current point which is an approximate solution. Meanwhile, a corrector yields an exact power flow solution on the PV Curve. Taking the derivative of the reformulated power flow equations, equation (4) becomes:

$$Z_\varphi d\varphi + Z_\Delta d\Delta + Z_\lambda d\lambda = 0 \quad (5)$$

Otherwise,

$$\begin{bmatrix} Z_\varphi & Z_\Delta & Z_\lambda \end{bmatrix} \begin{bmatrix} d\varphi \\ d\Delta \\ \mathrm{d}\lambda \end{bmatrix} = 0 \quad (6)$$

Meanwhile, $[d\varphi \quad d\Delta \quad \mathrm{d}\lambda]^{\mathrm{T}}$ is taken as the tangent vector upon which the predictor works. It is worthy of note that the addition of load parameter in the traditional power flow equations brings one more unknown variable and makes it difficult to get around equation (6). To get around this, one of the components of the tangent vector will be set to 1 or -1. This component is called the continuation parameter. Equation (7) becomes:

$$\begin{bmatrix} Z_\varphi & Z_\Delta & Z_\lambda \\ & a_n & \end{bmatrix} \begin{bmatrix} d\varphi \\ d\Delta \\ \mathrm{d}\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \quad (7)$$

Where a_n is a row vector with all elements equal to zero except for the nth element (continuation parameter) being equal to 1. The tangent vector is obtained by solving equation (7). The next predicted solution can be calculated as:

$$\begin{bmatrix}\varphi_{t+1}\\ \Delta_{t+1}\\ \lambda_{t+1}\end{bmatrix} = \begin{bmatrix}\varphi_t\\ \Delta_t\\ \lambda_t\end{bmatrix} + \delta\begin{bmatrix}d\varphi\\ d\Delta\\ d\lambda\end{bmatrix} \quad (8)$$

Where δ is the step size, which should be chosen taking into consideration for the convergence of the solutions and the computation speed.

4. RESULTS AND DISCUSSIONS

A continuation power flow results show that at 15th iteration the corrector solution (4.3698pu) was found to be too far from predictor value (1.7454pu). However, the maximum Loading Parameter 4.3698pu with a mismatch of 0.00324pu converged at 40th iteration search in 1.5016 seconds. To enable quicker convergence of the solutions and the computation speed, the step size was chosen to be 0.04. The maximum loadability with 4.369pu is shown in Figure 4. The result of CPF shows an excellent approach towards obtaining Margin to Voltage Collapse (4.1698p.u). The Current Operating Point (COP), the Saddle Node Bifurcation Point (SNBP) and the Margin to Voltage Collapse (MVC) of the 30Bus Nigerian National Grid (NNG) shown in Figure 5 are 2.5p.u, 6p.u and 3.5p.u respectively.

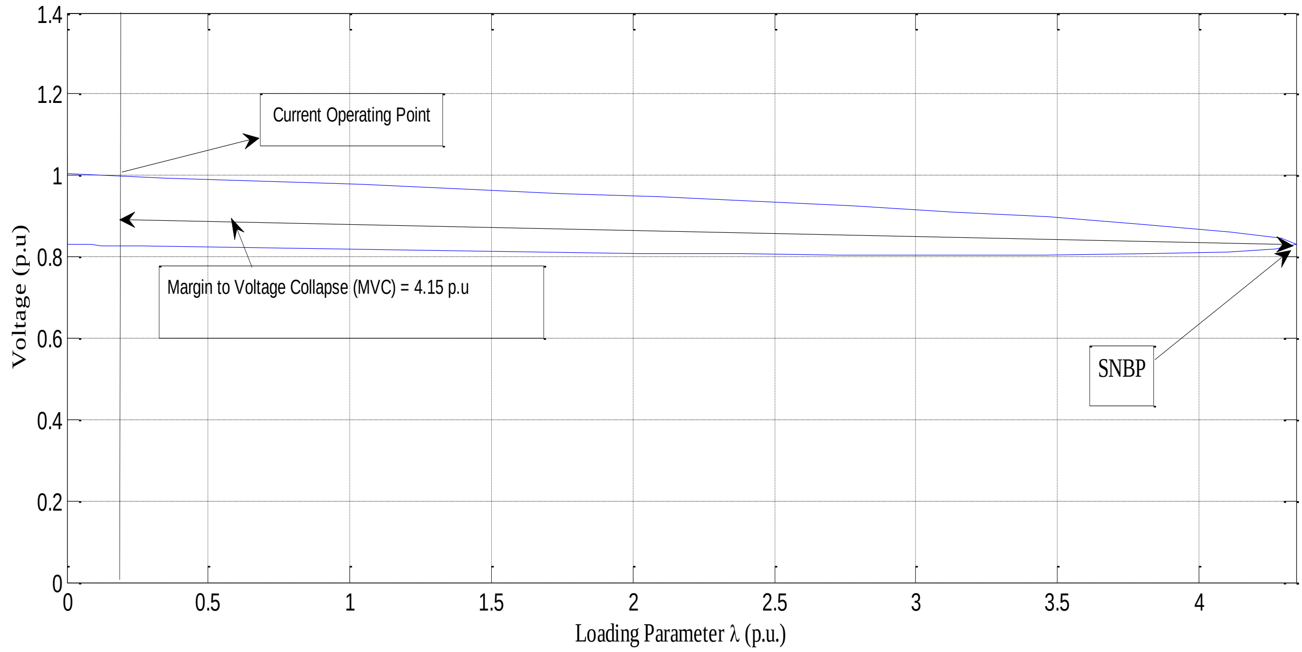

Figure 4: Margins to Voltage Collapse of the 10Bus NNG.

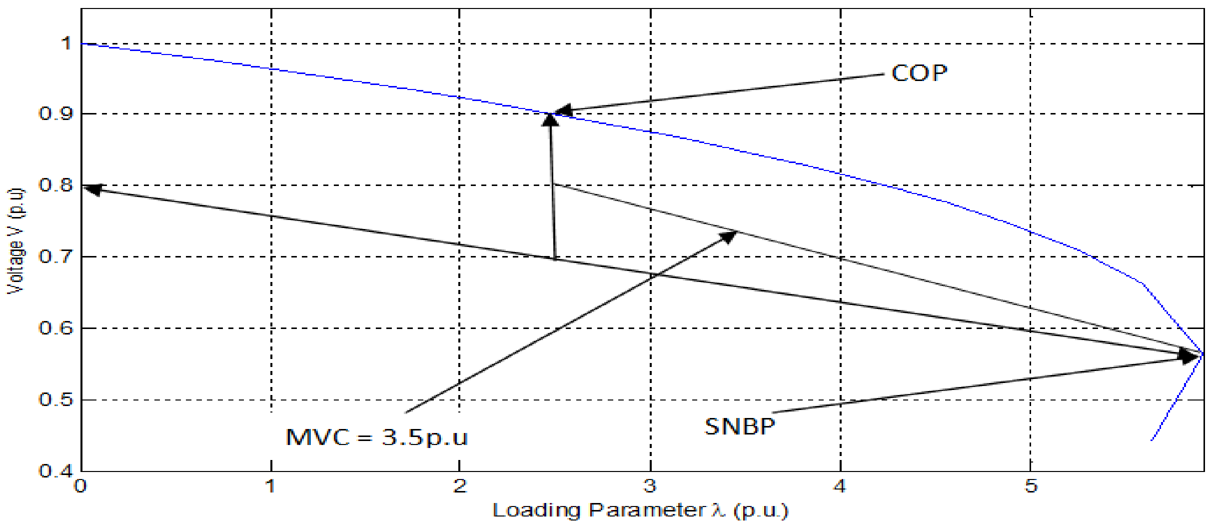

Figure 5: Margins to Voltage Collapse of the 30Bus NNG.

5. CONCLUSION

Sequence of events accompanying voltage instability that brings about Voltage Collapse in the significant parts of the Nigeria National Grid are identified as: outages of transmission lines and generators, high loadability of the transmission lines, the voltage drops that occur when active and reactive power flow through inductive reactance of the transmission network which limits the capability of the transmission network for power transfer and voltage support, reactive sources (generators) being too far from the load centers giving rise to low voltages at load buses. The MVC was estimated to be 4.1698p.u and 3.5p.u in the 10bus NNG and 30bus NNG respectively. Hence, Continuation Power Flow is an excellent approach in the determination of the MVC. Estimation of voltage collapse within the neighborhood of SNBP is useful in the power system network. In addition, in a risk-prone and beleaguered nation such as Nigeria, security checks evaluation of the power network is of paramount importance. The approach can be incorporated into user-friendly diagnostic tools for practical power systems and power utility applications in the determination of suitable remedial actions for instability and voltage collapse.

6. REFERENCES

[1] Transmission Company of Nigeria Oshogbo Daily report, 2017

[2] Onah, J. N. Madueme, T. C. and Ukwueze, V. C. "Contingency Evaluation of a Perturbed Electric Network", *International Journal of Electrical and Electronics Engineering,* Vol. 1, No. 5, pp. 136-142, 2015

[3] IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and Classification of Power System Stability", *IEEE Transaction on Power Systems,* Vol. 19, No. 3, pp. 1387-1401, 2004

[4] Beena, N. S. "Bifurcation Analysis for Voltage Stability of Power System", *National Conference on Recent Trends in Engineering & Technology*, India, pp. 11-16, 2011.

[5] Transmission Company of Nigeria Oshogbo Daily Operational Report, Saturday 29th September 2018

[6] TCN Oshogbo on Monthly Operational Report, 2018

[7] Ekwue, A. O, Wan, H. D, Cheng, D.T.Y and Song, Y. H. "Singular value decomposition method for voltage stability analysis on the National Grid system (NGC)", *Electrical Power and Energy Systems* Vol. 21, No. 6, pp. 425–432, 1999

[8] Samuel, I. Katende, J. Daramola, S. A. Awelewa, A. "Review of System Collapse Incidences on the 330-kV Nigerian National Grid", *International Journal of Engineering Science Invention,* Vol. 3, No. 4, pp. 55-59, 2014

[9] Ekwue, A. O, Cheng, D. T. Y, Song, Y. H and Wan, H. B. "Integrated Methods for Voltage Stability Analysis of the NGC System" *IEEE Colloquium on Voltage Collapse*, Savoy Place, London, pp. 1-6, 1997.

[10] Nwohu, M. N. "Estimation of bifurcation point in multi-bus system using generator reactive power limit approach", *Journal of Electrical and Electronics Engineering Research*. Vol. 2, No. 2, pp. 48-56, 2010

[11] Enemuoh, F. O, Onuegbu, J. C and Anazia, E. A. "Modal Based Analysis and Evaluation of Voltage Stability of Bulk Power System", *International Journal of Engineering Research and Development.* Vol. 6, No. 12, pp. 71-79, 2013

[12] Chandrabhan, S. and Marcus, G. G. "Determination of Power System Voltage Stability Using Modal Analysis" *IEEE International Conference on POWERENG*, Setubal, Portugal, pp. 381-387, 12-14th April, 2007.

[13] Cutsem, T. V. "A Method to Compute Reactive Power Margins with respect to voltage collapses", *IEEE Transaction on Power Systems*, Vol. 6, No. 1, pp. 145-156.