Tracing Power System Weak Nodal Shifts following Reactive Power Compensation

Bright, G. C. E[1] Uju, I. U[2] Onyedikachi, S. N[3]
[1,2,3]Department of Electrical/Electronic Engineering
[1,2]Chukwuemeka Odumegwu Ojukwu University, Uli. Anambra State [3]Nnamdi Azikiwe University, Awka. Anambra State

Abstract— The deficiency of reactive power especially at load buses result in poor voltage profile in these load buses which do not respond in the same measure owing to their individual reactive power need, adequacy of network reactive supply and their proximity to an adequate reactive source. The response of load buses to reactive power variation can be determines from various static methods suchas voltage drop index (VDI) or voltage-reactive power (V-Q) sensitivity analysis whose result provide a means to determine the choice location for reactive power compensation for voltage improvement and stability. This study using the Nigerian 330kV network determined the VDI of the networks load buses which was ranked based on the total VDI (TVDI). The work is an extension to the basic investigation for the optimal location of reactive power compensators within the Nigerian 330kV of 41 buses. In this case study, load bus active power is varied from a base case through five steps of 10% increments for which nodal voltages were determined. Using the result, TVDI for the load buses were computed and ranked with Yola, Omotosho and Maiduguri as the top three. Aided with this result, load flow analyses were executed for the individual and simultaneous shunt compensation at these buses and V-Q sensitivity analysis performed to ascertain how nodal weakness shifts between load bus following compensation. Each of the compensated cases when compared with the base case bus load flow result showed significant improvement in nodal voltage magnitude which justified the compensation but it did not eliminate bus voltage violation in the other previously violated buses. Following optimum nodal reactive compensation, the result from V-Q analysis shows that compensating a load bus of higher total voltage drop index shifts the bus participating in voltage instability to the next ranked load bus based on the TVDI. The deduction here is that independent shunt compensation for a higher ranked bus with respect to the bus participation factor or total voltage drop index shifts the responsibility of voltage instability to the next ranked load bus while compensating a lower ranked bus keeps the bus participation factor profile unchanged.

Keywords: VDI, TVDI, Voltage-Reactive Power (V-Q)

I. Introduction

One important aspect of power system stability analyses involves voltage stability which is defined as the ability of a power system to preserve steady-state bus voltages, before and after being subjected to a disturbance. Apower system is voltage stable when after a disturbance voltages at all buses in the system are within acceptable limits. One criterion for voltage stability is that at any given operating condition, the bus voltage magnitude increases as the reactive power injection at that same bus is increased for all network buses. Voltage instability on the other hand is the inability of the power system at normal operating condition to maintain steady acceptable voltage profile at all buses when subjected to a disturbance. This means that voltage instability occurs when a disturbance result in the progressive and uncontrollable deterioration of the power system bus voltages at normal operating conditions. This condition stems from the attempt by load dynamics to restore power consumption beyond the combine capacity of the transmission and generation facilities. According to [5] when a power system is subjected to a sudden increase in reactive power demand following a system contingency, the additional demand is met by the reactive power reserves of generators and compensators. If there is sufficient reactive reserve, the system will return to the initial or new acceptable and stable voltage level, however in the event of reactive power deficit, the system becomes voltage unstable and vulnerable to system collapse. Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to unacceptable voltage profile in a significant portion of the power system. These accompanying events often involve the actions and interactions of control and protective schemes and devices which are sensitive to the system disturbance. Following voltage instability, a power system is said to undergo voltage collapse if the post-disturbance equilibrium voltages at load buses are below acceptable voltage limits of ±5% of nominal value of high voltages. Reference [2] and [1] reports that the initiating events that leads to voltage collapse could have several dimensions of the forms, natural increase in system loads, sudden disturbance such as loss of generating units, loss of heavily loaded lines or transformers and the cumulative actions and interactions of control and protective schemes/devices. Although voltage instability and control are localized to buses, [10] and [13] opine that their impact is global with widespread consequences. Reference [11] observed that continuous voltage collapse results from reactive power deficit when the network loadings and the reactive power demand increases at specific areas or the entire system.

Unlike the dynamic voltage stability approach, the static voltage stability approach is commonly used in steady state research and online applications, providing an insight into stability problems with high speed of analysis. Reference [3] elucidates that steady state model such as the power flow model or a linearized dynamic model describing the steady state operation is best used for static voltage stability analysis. Static voltage stability study focuses of the existing power system equilibrium point. It requires that the disturbance is so small and the evolvement of the power is so slow that the dynamics of characteristic can be ignored. It regards power system transmission limits as the stability limit. Following reports and works by [7] and [9], there are many static analysis methods develop in literature. Most of them are base on the characteristics of the critical point, such as V-Q sensitivity analysis, Q-V modal analysis, singular value decomposition etc, some are base on multi solution of load flow equations, and others are originally derived from a two bus network and are extended to a complex bus system. Since the system dynamics that influence voltage stability are usually slow, many aspects of the problem of voltage stability can be effectively analyzed through static analysis methods which examine the viability of the equilibrium points specified by the given operating point of the power system.The voltage disparity between the sending and receiving ends of the power system exists on the account of reactive power imbalance between the generated and load reactive power within the network. That is for a bus, voltage magnitude is fairly directly proportional to the reactive power injection into that bus. A system is therefore, voltage unstable if of at least one bus in the system, the bus voltage magnitude decrease as the reactive power injection increases. This means that a system is voltage stable if the Voltage-Reactive power (VQ) sensitivity is positive and voltage unstable if the VQ sensitivity is negative for at least one of the buses.

Several other methods such as Use of Plot (Curves), Voltage Drop Index, Line Index Methods, Singular Value decomposition, Continuation Power Flow, Point of Collapse Method, Non Linear Programming technique, Modal Analysis have been postulated for static voltage stability to measure stability proximity estimating the point of voltage collapse. The static approach of voltage stability analysis is used to trace how weak nodes transfer is as voltage control is managed toward stability.

A. Modal Analysis

There are several methods developed for voltage stability analysis using the load flow Jacobian matrix. [12 and [8] submits that some of these methods exploit the singularity of the Jacobian matrix and are further based on reducing Jacobian determinants, identifying the critical buses using tangent vector as stated by [4] or by Modal analysis which involves computing eigenvalues and eigenvectors of reduced Jacobian matrix. In their 1992 publication, titled Voltage Stability using Modal Analysis, [6] proposed the Modal Analysis method for voltage stability studies. It is based on the computation of the smallest eigenvalues of the reduced Jacobian matrix of the steady state model of the power system and their associated eigenvectors. The eigenvalues are associated with a mode of voltage and reactive power variation. Using this method, the criterion for stability is defined that if all the eigenvalues are positive, the system is considered to be voltage stable. If one of the eigenvalues is negative, the system is considered to be voltage unstable. A zero eigenvalue of the reduced Jacobian matrix means that the system is on the verge of voltage instability. The potential voltage collapse situation of a stable system can be predicted through the evaluation of the minimum positive eigenvalues. The magnitude of each minimum eigenvalue provides a measure to know how close the system is to voltage collapse. By using the bus participation factor, the weakest bus can be determined, which is the greatest contributing factor for a system to reach voltage collapse situation

II. Method of Analysis

A. Steps to determine shifting weak node after reactive power compensation for voltage stability

To achieve Voltage Stability by Voltage Drop Index, the following steps are necessary

1) Define a base case and run the load flow of the network using any load flow technique
2) Extract the Bus Voltage magnitudes for pure load buses
3) Increase the active power component of network load by convenient percentage steps the generation can meet and repeat load flow analysis for at least five cases
4) Repeat (ii) for all the cases in (iii) and tabulate
5) Using the sorted voltage magnitude for the base case and first active load incremented case of (iii), determine the voltage drop index
6) Determine the VDI between the first and second, second and third, third and fourth and fourth and fifth active load incremented cases
7) Determine the Total VDI for each load bus and rankinascending order
8) From the most ranked, perform reactive power load compensation and V-Q sensitivity to seek weak node shift.

1) Test Network Description

The network contains 41 buses of which 18 are generator buses which supply a combined base load is 7460MW. There are 77 transmission lines for the network that operates at a voltage level of 330kV. For simplification, the impedance of the transformers has been ignored as the system is assumed to operate at steady state during the load analysis which is performed using the Newton Raphson iteration method. Only nodal voltage magnitude results for pure load buses which are 24 in numberare captured while the result of other buses including line flows and losses are ignored.

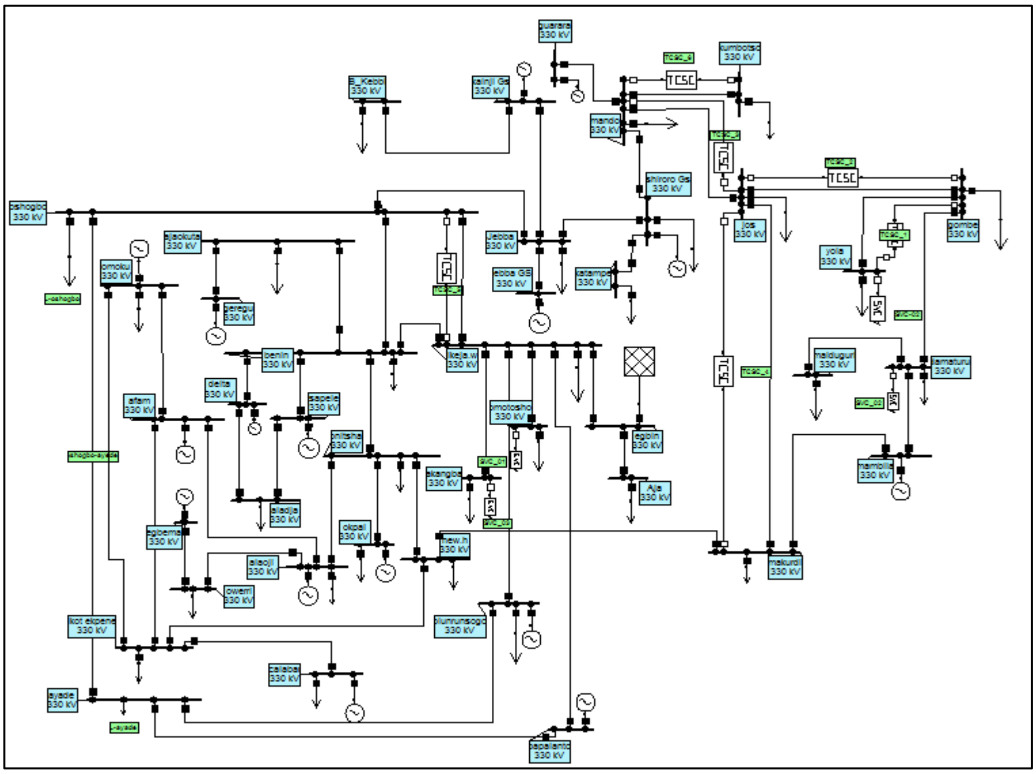

Fig. 1: One-Line Diagram of the Nigerian 41 bus 330kV Test Network

Load Bus Name	Active Load power	Nodal Voltage Magnitudes for base case and % active power Increments					
		Base Case	10%	20%	30%	40%	50%
Benin	357	0.9994	0.9994	0.9994	0.9993	0.9992	0.9991
Aja	355	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995
Ikeja West	329	0.9995	0.9996	0.9996	0.9995	0.9995	0.9995
Onitsha	315	0.9993	0.9992	0.9992	0.9991	0.9991	0.9990
Owerri	280	0.9995	0.9995	0.9995	0.9995	0.9994	0.9994
Akangba	270	0.9991	0.9991	0.9990	0.9990	0.9990	0.9989
New Haven	256	0.9990	0.9988	0.9987	0.9987	0.9986	0.9985
Ajaokuta	250	0.9992	0.9992	0.9992	0.9992	0.9992	0.9991
Jebba	250	0.9997	0.9997	0.9997	0.9997	0.9997	0.9996
Jos	250	1.0085	1.0060	1.0050	1.0040	1.0030	1.0030
Katampe	250	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996
Kumbotso	250	0.9574	0.9558	0.9542	0.9525	0.9507	0.9489
IkotEkpene	240	0.9993	0.9992	0.9992	0.9991	0.9991	0.9990
Ayade	239	0.9997	0.9997	0.9997	0.9997	0.9997	0.9996
Damaturu	230	0.9894	0.9838	0.9830	0.9821	0.9812	0.9802
Aladja	220	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
Oshogbo	201	0.9993	0.9993	0.9993	0.9993	0.9993	0.9992
Makurdi	200	0.9984	0.9979	0.9978	0.9977	0.9975	0.9974
Omotosho	200	0.9455	0.9430	0.9404	0.9376	0.9346	0.9314
BirninKebbi	180	0.9995	0.9995	0.9995	0.9994	0.9994	0.9994
Maiduguri	180	0.9404	0.9329	0.9306	0.9281	0.9255	0.9226
Yola	180	1.0000	0.8371	0.8277	0.8173	0.8056	0.7924
Gombe	160	0.9879	0.9735	0.9719	0.9702	0.9683	0.9662
Mando	357	0.9998	0.9998	0.9998	0.9998	0.9997	0.9997

Table 1: Bus voltage magnitude for base case and active power % increments

Table 1 shows the bus voltages at convergence for the load base case and all five cases of percentage active power increments from 10% through 50%. As the active load increased beyond the combined installed limit of the generators, analysis continued on an assumed basis that the slack generator had flexible limitless capability hence its output exceeded installed maximum capacity. The justification for this assumption is based on the fact that the focus is to determine the voltage drop value of pure load buses as their active power increased at unchanged reactive power. The computed Voltage Drop Index (VDI) for the load buses based on the result from table 1 is shown in table 2. The corresponding bus voltage drop index for a case with respect to a previous has been captured in the second column segment of the table with the caption voltage drop index with respect to load increment. The total voltage drop index (TVDI) is contained in the last column with the entire table sorted in ascending orders of the values of TVDI.

Load Bus Name	VDI1	VDI2	VDI3	VDI4	VDI5	TVDI
Aja	0.000	0.000	0.000	0.000	0.000	0.000
Aladja	0.000	0.000	0.000	0.000	0.000	0.000
Katampe	0.000	0.000	0.000	0.000	0.000	0.000
Ajaokuta	0.000	0.000	0.000	0.000	0.010	0.010
Ayade	0.000	0.000	0.000	0.000	0.010	0.010
BirninKebbi	0.000	0.000	0.010	0.000	0.000	0.010
Jebba	0.000	0.000	0.000	0.000	0.010	0.010
Mando	0.000	0.000	0.000	0.010	0.000	0.010
Owerri	0.000	0.000	0.000	0.010	0.000	0.010
Ikeja West	0.000	0.000	0.010	0.000	0.000	0.010
IkotEkpene	0.000	0.000	0.010	0.000	0.010	0.020
Onitsha	0.000	0.000	0.010	0.000	0.010	0.020
Oshogbo	0.000	0.000	0.000	0.000	0.010	0.010
Akangba	0.010	0.010	0.000	0.000	0.010	0.030
New Haven	0.000	0.010	0.000	0.010	0.010	0.030
Benin	0.000	0.000	0.010	0.010	0.010	0.030
Makurdi	0.010	0.010	0.010	0.020	0.010	0.060
Jos	0.070	0.070	0.080	0.080	0.080	0.380
Damaturu	0.071	0.081	0.092	0.092	0.102	0.440
Kumbotso	0.167	0.167	0.178	0.189	0.189	0.890
Gombe	0.144	0.164	0.175	0.196	0.217	0.900
Maiduguri	0.235	0.247	0.269	0.280	0.313	1.340
Omotosho	0.264	0.276	0.298	0.320	0.342	1.500
Yola	1.005	1.123	1.257	1.432	1.639	6.460

Table 2: Load Bus VDI in ascending order of TVDI

The load bus with the most significant TVDI is Yola (6.460) followed by Omotosho (1.500), Maduguri (1.340) and less significantly Gombe (0.900) and Kumbotso (0.890). The deduction of the VDI analysis provides basis for the optimum location for reactive power compensation in other to improve voltage values of the load buses with low voltage profile as seen from the base case result in column three of table 1.

B. Reactive Power Shunt Compensation and Weak Node Shifts

1) Shunt compensation at Yola

With load bus at Yola having the highest TVDI, it is the prime location for shunt compensation which is achieved with an SVC. The bus load flow result for the nodal voltage magnitudes for the compensation at Yola shown in the third column of table 3. The result show that most load buses had improved bus voltage magnitude. Therefore the significance of this compensation may be observed at the three buses with the highest tendency for lower limit bus voltage violations, namely; Yola, Omotosho and Maiduguri. With shunt compensation 139MVar at Yola, the base case bus voltage magnitude as shown in table 3 improved from 0.8456pu of the base case to the expected nominal 1pu value which is the equivalent of 330kV. However, due to distance between them, Omotosho remained affected with value of 312.01kV which is below the minimum voltage magnitude while there was slight voltage improvement at Maiduguri from 0.9351pu to 0.9404pu. With this compensation, the participation of load bus to low voltage profile and instability shifted from Yola to Omotosho as can be seen in the Voltage-Reactive power sensitivity bar chart of figure 2 which is the load bus participation factors to voltage instability.

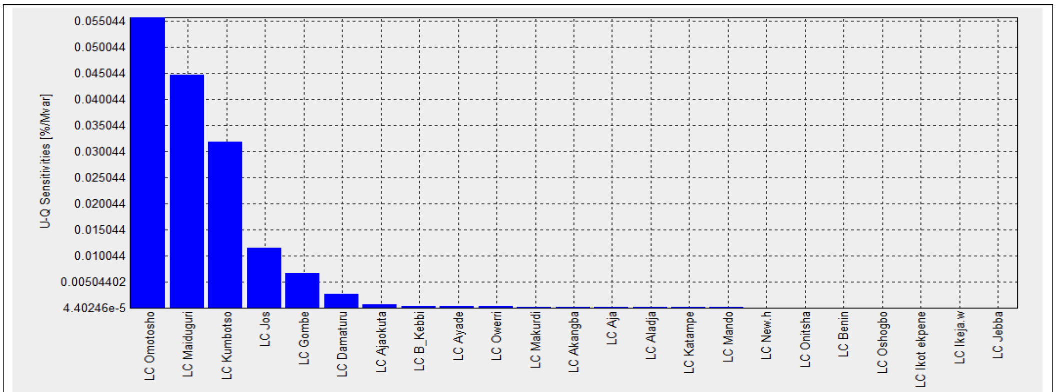

Fig. 2: Load Bus Participation factor for Voltage stability using V-Q sensitivity with shunt compensator at Yola

2) Shunt compensation at Omotosho

It is obvious that the reach of the reactive power compensation at Yola did not improve voltage at Omotosho. The needed compensation at Omotosho results in voltage magnitudes for the load busesare shown in fourth column oftable 3 following a shunt compensation of 104MVar. The voltage magnitude at this bus improved from 0.9455pu to the nominal 1pu (330kV) without a resultant voltage improvement at Yolawhich remained at 0.8456pu. Following this shunt compensation at Omotosho, as shown in figure 3 the bus participation factor due to the voltage sensitivity of load buses to reactive power variation remained with load bus at Yola which originally had the highest TVDI.

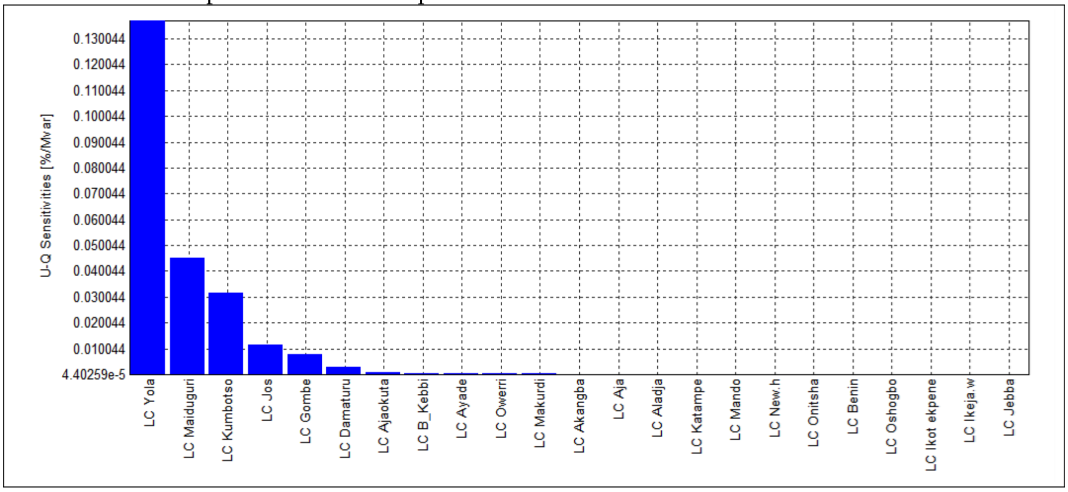

Fig. 3: Load Bus Participation factor for Voltage stability using V-Q sensitivity with shunt compensator at Omotosho

3) Simultaneous Shunt compensation at Yola and Omotosho

As seen from the above compensations, the most significant bus participation factors alternates between Yola to Omotosho when the either is compensated. The reach of compensation is limited to the neighboring buses and the lack of proximity between Yola and Omotosho makes the independent shunt compensation at these buses inevitable. With simultaneous shunt compensation of 104MVar and 139MVarat Yola and Omotosho respectively, the fifth column of table 3 shows the load bus voltage magnitudes. Compared with the base case bus voltage magnitude profile of column one, table 3 indicates only one bus lower limit voltage magnitude violation at Maiduguri 0.9404pu in this combined compensation case. The most significant bus participation factor shifted from Yola and Omotosho being compensated to Maiduguri with Kumbotso trailing significantly.

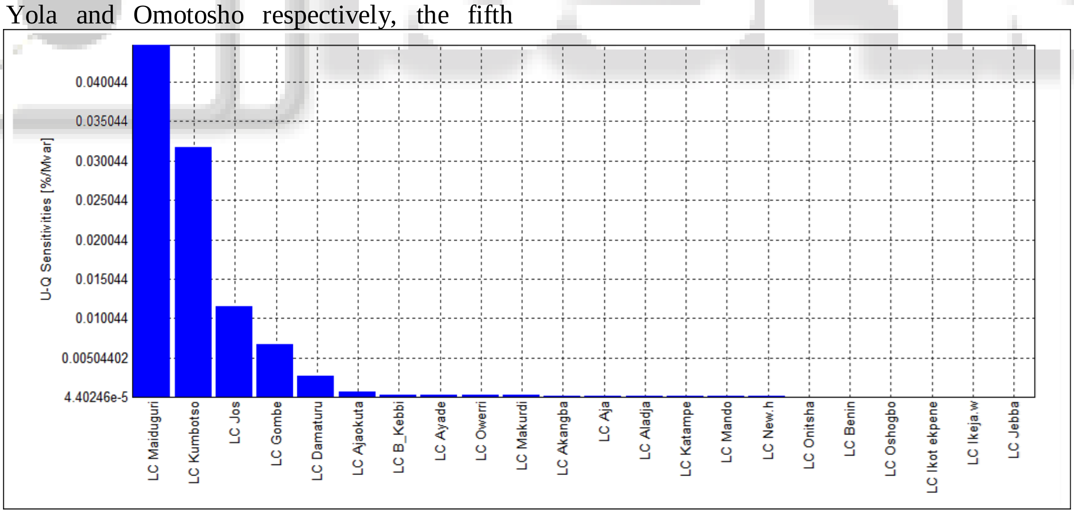

Fig. 4: Load Bus Participation factor for Voltage stability using V-Q sensitivity with shunt compensators at Omotosho&Yola.

4) Shunt compensation at Maiduguri

The previous compensations did not yield any significant improvement in the voltage magnitude of Maiduguri, hence the need to investigate the impact of the shunt compensation at this load bus. Compensated with an injection of 154.26MVar at Maiduguri, column six of table 3 shows the voltage magnitude profile of the load buses during this compensation. However, this compensation did not yield any improvement to the load bus voltage of Omotosho and Yola which both remained below the 0.95pu lower limit with0.9455pu and 0.8518pu respectively. Essentially, only two bus voltage magnitudes were violated as shown in table 3 as Yola and Omotosho in figure 5 retained the buses with the highest bus participation factors of the network with respect to the proximity of the network to voltage instability.

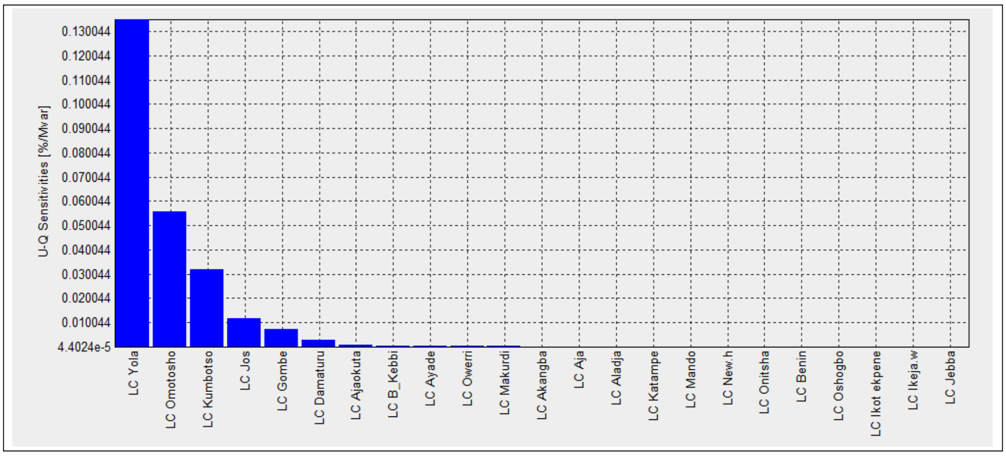

Fig. 5: Load Bus Participation factor for Voltage stability using V-Q sensitivity with shunt compensators at Maiduguri

5) Shunt compensation at Yola, Omotosho and Maiduguri

From the result of previous individual and simultaneous shunt compensations, the reach of compensation had been limiting to the extent that only the compensated bus and few of the buses with proximity to the compensated bus experience improvement in their bus voltage magnitudes. Consequently, there is need for the concomitant reactive power compensation at Yola, Omotosho and Maiduguri. With the injection of 134.857MVar, 104.051MVar and 142.265MVar respectively to these buses, the nominal value of 1pu was noticed at each of these compensated nodes as seen in column seven of table 3. It is instructive to note that there was no load bus voltage limit violation during these compensations. From figure 6, Kumbotso bus had the next bus participation value as an indication to the network voltage instability. However, there is no bus voltage limit violation when these three buses are compensated with appropriate sized shunt compensators.

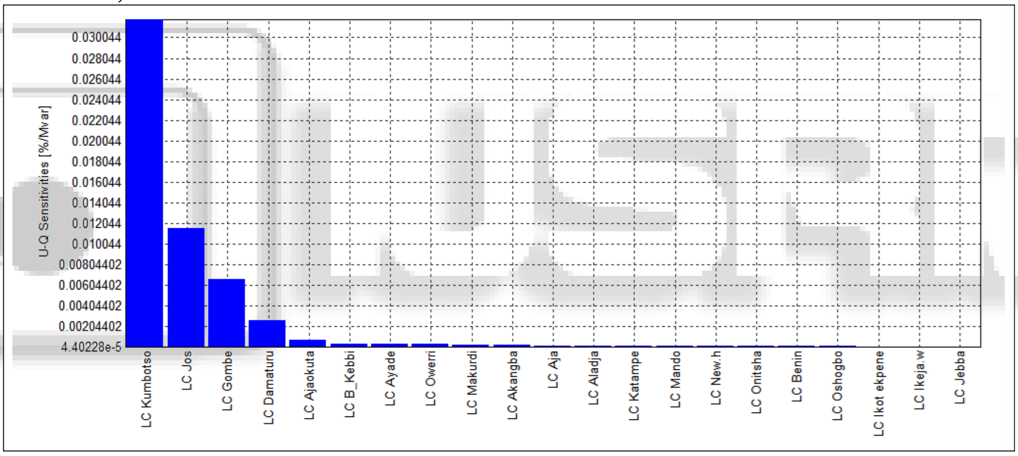

Fig. 6: Load Bus Participation factor for Voltage stability using V-Q sensitivity with shunt compensators at Yola, Maiduguri & Omotosho

Bus Name	Load flow load bus Nodal Voltages during					
	Base Case	Com/Yola	Com/Omo	Com/Mai	Com/Yola-Omo	Com/Yola-Omo-Mai
Aja	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995
Ajaokuta	0.9992	0.9992	0.9992	0.9992	0.9992	0.9992
Akangba	0.9990	0.9990	0.9991	0.9990	0.9991	0.9991
Aladja	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
Ayade	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
Benin	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995
BirninKebbi	0.9995	0.9995	0.9995	0.9995	0.9995	0.9994
Damaturu	0.9845	0.9894	0.9845	0.9892	0.9894	0.9935
Gombe	0.9749	0.9879	0.9749	0.9795	0.9879	0.9917
Ikeja West	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996
IkotEkpene	0.9992	0.9993	0.9992	0.9993	0.9993	0.9994
Jebba	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
Jos	1.0064	1.0085	1.0064	1.0073	1.0085	1.0092
Katampe	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996
Kumbotso	0.9574	0.9574	0.9574	0.9574	0.9574	0.9574
Maiduguri	0.9351	0.9404	0.9352	1.0000	0.9404	1.0000
Makurdi	0.9980	0.9984	0.9980	0.9984	0.9984	0.9988

Mando	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998
New Haven	0.9988	0.9990	0.9988	0.9990	0.9990	0.9992
Omotosho	0.9455	0.9455	1.0000	0.9455	1.0000	1.0000
Onitsha	0.9992	0.9993	0.9992	0.9993	0.9993	0.9993
Oshogbo	0.9993	0.9993	0.9993	0.9993	0.9993	0.9994
Owerri	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995
Yola	0.8456	1.0000	0.8456	0.8518	1.0000	1.0000

Table 3: Load bus Voltage Magnitude (pu) for Base and compensated cases

III. CONCLUSION

In every power system network with voltage instability, there is often an imbalance between generated and consumed reactive power. The deficiency of reactive power especially at load buses result in poor voltage profile in them. However, load buses do not respond in the same manner due to their reactive power need, proximity to reactive source and adequacy of network reactive supply. The sensitivity of load nodes to reactive power variation can be determined from voltage drop index (VDI) or voltage-reactive power (V-Q) sensitivity analysis. When ranked, the result of VDI or V-Q analysis provides a means to determine the choice location for reactive power compensation for voltage improvement and stability. This study using the Nigerian 330kV network determined the VDI of the networks load buses which was ranked based on the total VDI (TVDI). Following optimum nodal reactive compensation, the result from V-Q analysis shows that compensating a load bus of higher total voltage drop index shifts the bus participating in voltage instability to the next ranked load bus based on the TVDI. The deduction here is that independent shunt compensation for a higher ranked bus with respect to the bus participation factor or total voltage drop index shifts the responsibility of voltage instability to the next ranked load bus while compensating a lower ranked bus keeps the bus participation factor profile unchanged. Secondly, for voltage magnitude violated load bus located further from a reactive source, only compensation at such bus can improve its voltage profile as load increases. The state of the power system analyzed in this work was limited to the steady state condition. The compensating FACT device however has dynamic capability, hence the recommendation for further study could focus on the dynamic compensating requirement and performance of the network, as load vary dynamically. Secondly, the analysis proceeded with the assumption that all network components remained intact without any form of contingency such as line outage. Subsequent study could extend to the investigation of post-contingency compensation capability following the line or/and generator contingency.

REFERENCES

[1] Ajjarapu V., (2006). “Computational Techniques for Voltage Stability Assessment and Control” Springer,
[2] Althowibi F.A., Mustafa M.W., (2013) “Power System Voltage Stability: Indications, Allocations and Voltage Collapse Predictions”, Internal Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering Vol.2, Issue 7, Page 19.
[3] Claudia Reis, MacielBarbosa F.P., (2006)“A Comparison of Voltage Stability Indices”, IEEE MELECON 2006, May 16-19, pp 1007-1010.
[4] De Souza A.C.Z., Canizares C.A., Quintana V.H., (1997). "New techniques to Speed up Voltage Collapse computations using Tangent Vectors," IEEE Trans. Power System, vol. 12, pp. 380–1387
[5] Dorin Bică, (2012). “Steady-state Analysis of Voltage Stability by Reactive Participation Factor”.6thedition of Interdisciplinary in Engineering.International Conference. pp 260-265.
[6] Gao B., Morison G.K., Kundur P. (1992)“Voltage Stability Evaluation Using Modal Analysis” IEEE, Transactions on Power Systems, Volume 7.
[7] Kessel P., Glavitsch H. (1986) “Estimating the Voltage Stability of a Power System” IEEE, Transactions on Power Delivery, Vol.PWRD-1.
[8] Prada R.B., De Souza A.C.Z., Filho X.V., Massaud A.G., Oliveira J.C.C., (1991) "Voltage Stability: Phenomena Characterization based on Reactive Control effects and System Critical Areas Identification," Proceedings of the third Sepope meeting, Belo Horizonte, Brazil,
[9] Shmuel, S. O. (1998). Transmission Pricing and Congestion Management: Efficiency, Simplicity and Open Access. USA: University of California, Berkeley.
[10] Van Cutsem, T. (2008). Voltage Instability. In M. Crappe, Electric Power Systems (1 ed., pp. 185-188). Hoboken: ISTE Ltd and John Wiley & Sons, Inc, Thierry.
[11] Vishnu, J., Rishi, M., J, T., Sasidharan, S., Vipindas, P., Sebin, J., & Chittesh, V. C. (2014). Maximum Loadability Assessment of IEEE 14 Bus Systems by using FACTS Devices Incorporating Stability Constraints. Second IRF International Conference.2, pp. 88-94. Cochin, India: IRAJ Publication.
[12] Young-Huei, H., P. Ching-Tsai and L. Wen-Wei, 1997.Fast calculation of a voltage stability index of power systems. IEEE Trans. Power Syst. 12(4): 1555-1560.
[13] Zima, M., M. Larsson, P. Korba, C. Rehtanz and G. Andersson, (2005). Design Aspects for Wide-Area monitoring and control systems. Proc. IEEE, 93(5):980-999