Predicting Weak Nodes for Reactive Power Compensation in Nigerian Power Network

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Abstract- Identifying weak buses is imperative to avoid redundant reactive power compensation in order to improve reactive power in any network. As active power demand is increased at fixed reactive power, the matching reactive power support depletes resulting in poor voltage profile due to voltage drops along the transmission lines connecting sending and receiving end buses. As a result, load buses would respond differently due to their varying proximity to power sources and each load bus could have a unique voltage drop index following series of active power increments. The work is a basic investigation for the optimal location of reactive power compensators within the Nigerian 330kV of 41 buses. With power varied from a base case through five steps of 10% increment from the previous, the result of the total voltage drop index ranked Yola, Omotosho and Maiduguri as the locations for shunt compensation. Aided with this result, load flow analyses were executed for the individual and simultaneous shunt compensation at these buses. In each of the individual compensation, the reach of influence of the compensator was limited to the compensated bus and the nearest bus neighbors attaining the nominal value of 330kV or almost near it. Each of the compensated cases when compared with the base case bus load flow result showed significant improvement indicating that the compensation was worth it. However, the individual compensation or simultaneous compensation at two of the three buses did not eliminate bus voltage violation in the other two or one bus as the case may be. The best steady state operation case recorded when the trio of buses at Maiduguri. Omotosho and Yola were all shunt compensated with SVC. No bus in the network had any form of bus voltage violation as the least bus voltage was well within the prescribed limit.

Indexed Terms - Nigeria power system, Reactive compensation, Voltage drop, Voltage stability, voltage stability improvement

I. INTRODUCTION

Good quality power supply requires the voltage and current waveform of the ac system to be with little or no distortion. Unfortunately due to the presence of these non-linear loads, the waveforms end up being distorted. However, a power system is expected to operate under varying conditions, from no-load to overloading to short-circuit with the quality of supply maintained over these range of conditions according to Wadhwa, (2013). As system loads vary, the reactive power requirements of the transmission system varies expectedly.

The ability of a system to remain in a state of equilibrium and to return to that original state or a new acceptable equilibrium state after a disturbing force has been defined by Ajjarapu, (2006) as power system stability. In contrast, power system instability is the inability of the powers system to remain or be restored to a state of equilibrium following a disturbance. The complete study of operational power system steady stability is covered within three broad aspects of stability, namely; Voltage Stability analysis, Frequency Stability and Rotor angle stability. According to Althowibi et al (2003) and Cutsen et al. (2008), frequency and Rotor angle stabilities are sensitive to active power interactions unlike voltage stability which depends on reactive power interactions and is reflected on the nodal voltage magnitude and profile. Garng and Zhang (2001) opine that the occurrence of steady state voltage instability is about the most severe problem in any operational power system of a large size or integrated complexity. *Lofetal (1992) and Young-Hueiet al. (1997*) independently suggest that ensuring a voltage stable power system is not only challenging due to the thermal capability or steady state voltage stability limits but that voltage stability is a topnotch priority. The existing voltage disparity between the sending and receiving ends of the power transmission system nodes is due to the reactive power imbalance between generated and consumed reactive power within the network. This voltage profile can be improved by transmitting reactive power to the load from a remote source. However, the practice is obsolete and vanishing as it requires larger sized conductors to implement. The presence of reactive power flow on the transmission line may significantly cause voltage to fluctuate along transmission lines, particularly for long transmission lines, Anumuka & Mbachu (2013). Since reactive power cannot be economically and effectively transmitted over long distances, voltage control has to be achieved by using special devices dispersed throughout the system. Again, rotational and inductive loads like motor require reactive power to convert the flow of electrons into useful work and provide the needed coupling fields for energy devices. Accordingly, Rudrangshu, et al., (2015) suggests that in order to alleviate some of these problems associated with reactive power, compensation has to be incorporated manually or automated into the system to guarantee an efficient delivery of real power through transmission lines to the loads and to maintain the voltage at the load buses. According to Whitaker (2007), reactive power compensation is the generation or absorption of a suitable quantity of reactive power devices, either capacitive or inductive; to achieve one or more desired effects in an electric power system. These effects include improved voltage profiles, enhanced stability, and increased transmission capacity. The devices are either in series or in shunt (parallel) with the load(s) at one or more points in the power system network. Consumer loads (residential, commercial and industrial sectors) impose real and reactive power demand, depending on their characteristics.

Theory of Load Compensation

According to Kundur, (1990), depending on the load current, transmission lines are known to either absorb or supply reactive power. At loads below the natural (surge impedance) load of the transmission lines, the voltage levels soar and as a result, the line produces a net reactive power. On the other hand, when the load is above the natural load, the voltage level dips and the lines absorb reactive power. However, for flat voltage profile under an ideal situation, the reactive power absorbed should be equal to the reactive power generated. But because of the presence of losses, the reactive power in the system keeps varying. So in order to maintain non-fluctuating voltage profile, the reactive power generation is simultaneously controlled or adjusted with respect to an individual load. Wadhwa, (2013), advocates that transmission network should be designed based on active power transfer capability and the reactive power should be met locally by installing shunt compensating devices (capacitor and inductors) at the point of load where they are needed in order to avoid the cost of having to install large conductor and also to reduce transmission line losses. This he said is the principle behind power factor correction. Again, in order to avoid the flow of negative sequence current in the system and consequently improved on the stability of the system, the three-phase system should be operated under balanced condition which is referred to as load balancing.

This technically and economically more viable alternative practice implies the operation of a reactive power compensating device at proximity to the load centre and termed load compensation. Load compensation is the management of reactive power at the load end to achieve improved quality of supply with respect to power factor levels and voltage management. The practice in load compensation is to install the compensating device to the load centre and then adjust the reactive power of the device in order to improve the load voltage profile, power factor connection and load balancing. Synchronous condensers and capacitor banks had long provided near load compensation but the inflexibility, cost and maintenance requirements makes the newer implementation by Flexible Alternating Current Transmission Systems (FACTS) devices more attractive. One basic form of FACTS is the Static Var Compensator (SVC). Though relatively expensive with reference to comparative size, FACTS compensators have the advantage of speed and coordination with less or no operator's coordination as their operation and response can be automated. As with synchronous condensers and capacitor banks whose effects can be conveyed through connecting transmission lines, the effect of FACTS can also be felt from distant locations within the network justifying the need to eliminate operational redundancy. Consequently, it is not only technically and economically instructive to know the number and size of compensating devices needed within the network but also to be certain of the best load centre location for optimum operation in order to avoid operational redundancy of reactive power compensation for voltage stability. It is opined that ascertaining the optimum location may well provide clues to the number, nature and size of the compensating devices. The pertinent problem is therefore to determine these locations which are essentially weak nodes.

In order to ascertain the location of load compensators for enhanced performance of power system, performing voltage stability analysis of that network is indispensable. One of the chief causes of disproportionate voltage profile and voltage instability is the voltage drop that occurs when both active and reactive power flow through the inductive reactance of a transmission network. The effect includes reducing the transmission network power transfer capacity and voltage support thereby making the network unable to meet the reactive power demands. Essentially, there is often a significant drop between the voltages of the sending and receiving end nodes due to losses on the transmission lines connecting. Therefore, measuring these nodal voltage drops and assigning a cumulative index could provide clues to those buses that are weak in voltage magnitude while ranking the resulting list identifies the weakest nodes and provides information on priority location of load compensation of reactive power for voltage stability improvement.

Classes of Compensators

Compensators are classified as passive and active compensators. The main essence of shunt compensation is to regulate voltage while series improves power transfer capability of the transmission line. Shunt reactors and capacitors, and series capacitors provide passive compensation. Shunt reactors are applied to compensate for the undesirable voltage effects associated with line capacitance particularly to limit voltage rise on open circuit or light load. Shunt capacitor supplies part of the reactive power required by an inductive load so that the reactive power transmitted over the line are reduced, thereby maintaining the voltage across the load within a certain desirable limit. Series capacitors reduce the transfer reactance of line to which the capacitor is connected thereby increasing the maximum real or active power that can be transmitted, and reduces the effective reactive power (I^2X) loss and the reactive power produced by a series capacitor increases with increasing power transfer.

Static VAR Compensators (SVCs)

SVCs are shunt-connected static generators and/or absorbers with varied output used to control specific parameters of the electric power system. According to IEEE specification as observed by Essays UK (2013), SVCs are shunt connected static VAR generators/absorbers whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters typically bus voltage of the electrical power system. Anulekhaet al (2012) opine that the SVC is an automated impedance matching device, designed to bring the system closer to unity power factor. If the power system's reactive load is capacitive (leading), the SVC will use reactors (usually in the form of Thyristor-Controlled Reactors) to consume VARs from the system, lowering the system voltage to nominal. Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage.

Voltage Drop Index Analysis

According to Saber et al (2012), Voltage Drop Index (VDI) represents the drop of voltage at each bus as the active power component at each of the pure load bus is increased. For any bus i, VDI is mathematically defined as

$$VDI_i^r = \frac{\left| |v_i|^{r+1} - |v_i|^r \right|}{|v_i|^r} \tag{1}$$

$i = 1, 2, 3, \cdots, n_{PQ}$ and $r = 0, 1, 2, \cdots, s$; for s number of percentage real power increase for n_{PQ} pure load buses in the network; r= the stage of load flow analysis after load increase upon performing the last (s) percentage load increase load flow analysis and computing the requisite VDI, the Total VDI for any bus can be computed with

$$TVDI_i = \sum_r^s VDI_i^r \qquad (2)$$

When all load bus TVDI are computed, then they are ranked in descending order and the most ranked is the one with most influential in the low voltage profile of the network and it is the best location for load compensation.

II. METHOD OF ANALYSIS

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

- i. Define a base case and run the load flow of the network using any load flow technique
- ii. Extract the Bus Voltage magnitudes for pure load buses
- iii. Increase the active power component of network load by convenient percentage steps the generation can meet and repeat load flow analysis for atleast five cases
- iv. Repeat (ii) for all the cases in (iii) and tabulate
- v. Using the sorted voltage magnitude for the base case and first active load incremented case of (iii), determine the voltage drop index
- vi. Determine the VDI between the first and second, second and third, third and fourth and fourth and fifth active load incremented cases
- vii. Determine the Total VDI for each load bus and rank in ascending order
- viii. Perform load compensation using SVC: Beginning that the top of the ranking, suggest reactive power compensation size based on the reactive power requirement at base case perform load flow analysis; Note the resulting bus voltage magnitude for improvement.

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 number are captured while the result of other buses including line flows and losses are ignored.

III. RESULT OF ANALYSIS

Using the result shown in table 1, which is the voltage magnitudes of the base case and those of the five step increments (10% to 50%)of active power of the load buses, the computed VDI and TVDIs for the load buses is shown in table 3.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. The load bus with the most significant TVDI is Yola. Then there is Omotosho, Maiduguri, Kumbotso, Gombe and Damaturu all with values that are comparatively significant. The deduction of the VDI analysis provides the choice location for reactive power compensation in other to improve voltage values of the buses and the network at large.

Effect of Reactive Power Shunt Compensation of Weak Buses

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 Blue bars) is compared to that during the base case (green bars) in figure 2. 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 figure 2 improved from 84.56% to the expected nominal value 100% 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 93.51% to 94.04%.

Table 1: Computation of VDI from bus voltage magnitude for increasing load real power

Load Bus Name	Nodal Voltage Magnitudes					
	BC	**10%**	**20%**	**30%**	**40%**	**50%**
Benin	329.81	329.8	329.8	329.77	329.74	329.7
Aja	329.84	329.84	329.84	329.84	329.84	329.84
Ikeja West	329.85	329.87	329.87	329.84	329.84	329.84
Onitsha	329.76	329.74	329.74	329.7	329.7	329.67
Owerri	329.83	329.84	329.84	329.84	329.8	329.8
Akangba	329.69	329.7	329.67	329.67	329.67	329.64
New Haven	329.68	329.6	329.57	329.57	329.54	329.51
Ajaokuta	329.74	329.74	329.74	329.74	329.74	329.7
Jebba	329.9	329.9	329.9	329.9	329.9	329.87
Jos	332.82	331.98	331.65	331.32	330.99	330.99
Katampe	329.88	329.87	329.87	329.87	329.87	329.87
Kumbotso	315.95	315.41	314.89	314.33	313.73	313.14
Ikot Ekpene	329.78	329.74	329.74	329.7	329.7	329.67
Ayade	329.91	329.9	329.9	329.9	329.9	329.87
Damaturu	326.5	324.65	324.39	324.09	323.8	323.47
Aladja	329.91	329.9	329.9	329.9	329.9	329.9
Oshogbo	329.78	329.77	329.77	329.77	329.77	329.74
Makurdi	329.48	329.31	329.27	329.24	329.18	329.14
Omotosho	312.01	311.19	310.33	309.41	308.42	307.36
Birnin Kebbi	329.82	329.84	329.84	329.8	329.8	329.8
Maiduguri	310.34	307.86	307.1	306.27	305.42	304.46
Yola	330	276.24	273.14	269.71	265.85	261.49
Gombe	326.01	321.26	320.73	320.17	319.54	318.85
Mando	329.95	329.93	329.93	329.93	329.9	329.9

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 magnitude shown in brown bars in figure 2 following a shunt compensation of 104MVar. The voltage magnitude at this bus improved from 94.55% to 100% (330kV) without a resultant voltage improvement at Yola remained at 279.04kV.

Table 2: Load Bus VDI in ascending Order 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
Birnin Kebbi	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
Gombe	0.144	0.164	0.175	0.196	0.217	0.900
Kumbotso	0.167	0.167	0.178	0.189	0.189	0.890
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

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 other 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, figure 2shows bus voltage magnitudes in Red bars. Compared with the base case bus voltage magnitude profile, figure 2 indicates only one bus lower limit voltage magnitude violation at Maiduguri (94.04%) in this combined compensation case.

Shunt Compensation at Maiduguri

The previous compensations did yield any significant improvement in the voltage magnitude of Maiduguri, hence the need to investigate the impact of the shunt at this load bus. Compensated with an injection of 154.26MVar at Maiduguri, figure 2 shows yellow bars representing the nodal voltages during this compensation reflecting. However, this compensation did not yield any improvement to the load bus voltage of Omotosho and Yola which both remain below the 95% lower limit at 94.55% and 85.18respectively.

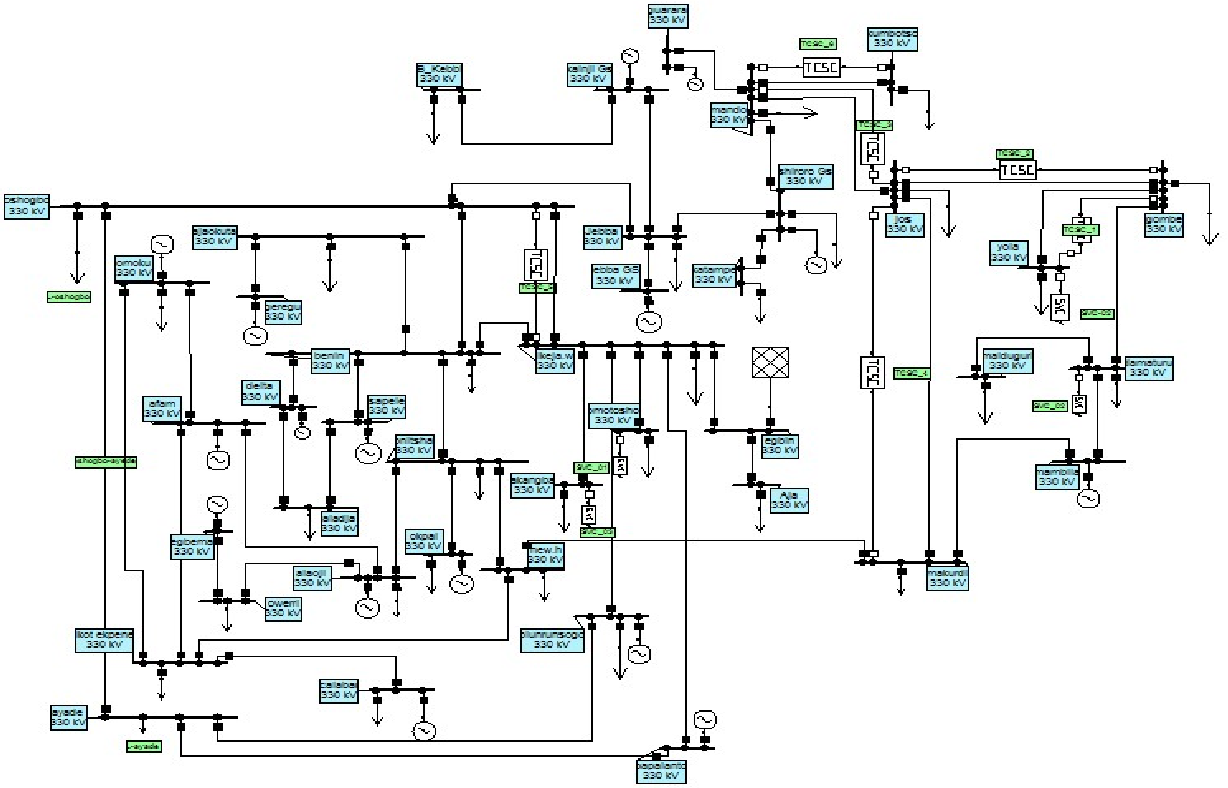

Figure 1: One-Line Diagram of the Nigerian 330kV Test Network

Compensation at Yola, Omotosho and Maiduguri

From the result of previous individual and simultaneous shunt compensations, the reach of compensation had been limiting so much that only the compensated bus and few of the neighboring buses experience improvement in their bus voltage magnitudes, hence the need for the concomitant reactive power compensation at Yola, Omotosho and Maiduguri. With the injection of 134.857MVar, 104.051MVar and 142.265MVar respectively, 330kV were noticed at these three buses as shown in black bars in figure 2. It is instructive to note that there was no load bus voltage limit violation during these compensations.

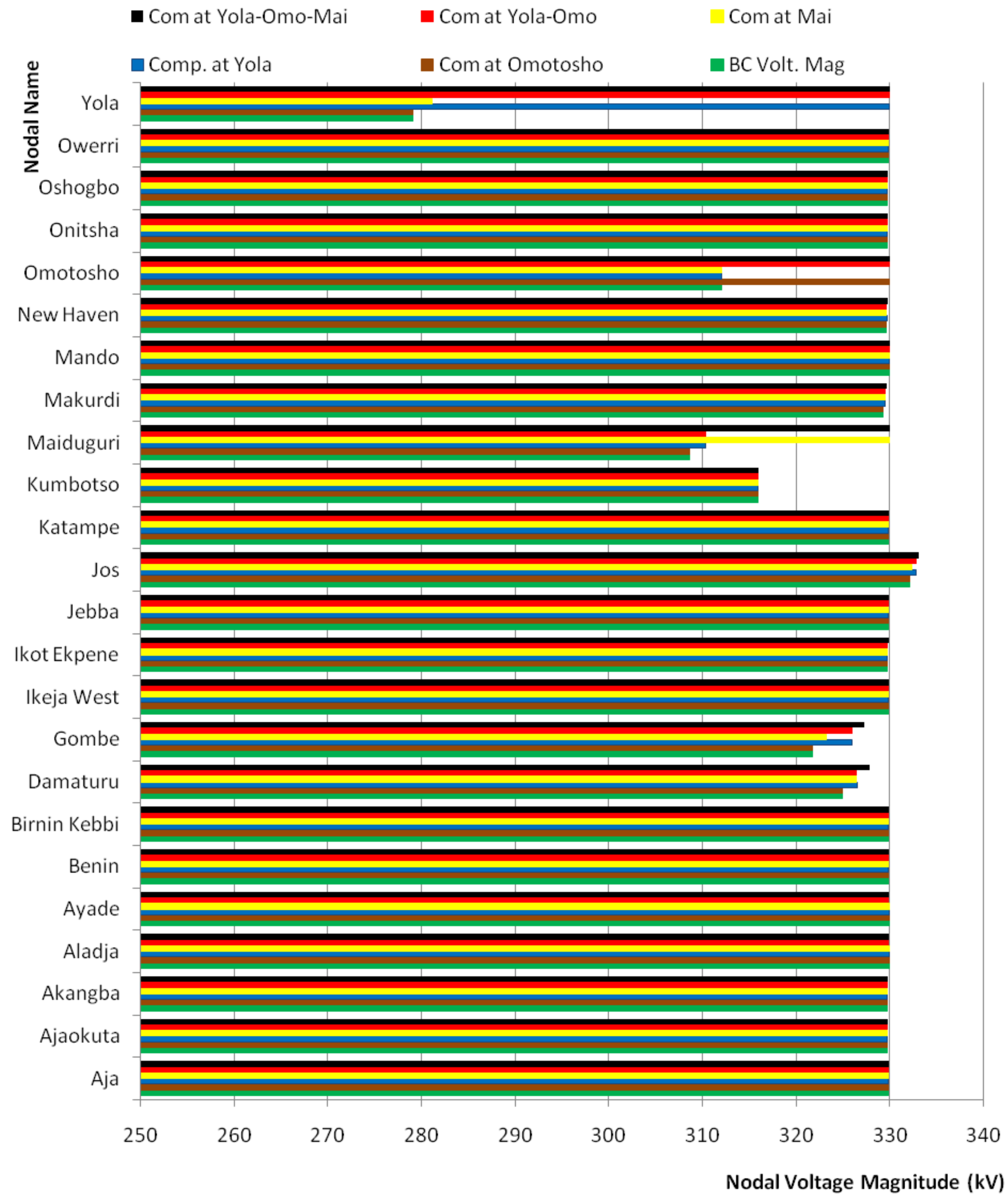

Figure 2: Nodal Voltage Magnitudes for Base and Shunt Compensated cases

IV. CONCLUSION

The Voltage drop index was used to identify the network weak buses on the bases that as active power demand increases in the face of fixed reactive power, voltage profile of the network would deplete owing to unmatched reactive power supply and the voltage drop along the transmission line between the buses at the sending and receiving ends. For the VDI computation, the network of 41 buses were used which has 24 pure load buses whose active power values were increased through five steps of 10% of their base case values which totaled 7459.72MW. The AC load flow result at base case showed voltage magnitude lower limit voltage violations at bus Yola, Omotosho, Maiduguri and Kumbotso. As loading increased through five steps of 10% each, there was significant voltage magnitude deterioration at load buses reflecting the depletion of reactive component supply which remained fixed at 3951MVar from base case. As expected, load buses are the most prone to poor voltage profile as against generator and voltage control buses which have automatic reactive power response mechanism to keep voltage magnitude constant. The top TVDI ranking in descending include Yola, Omotosho, Maiduguri, Kumbotso and Gombe. The load bus at Yola requires 180MVar reactive power which is served insufficiently by a transmission line by Jos through a single line at Gombe whose voltage magnitude is below the lower limit. Besides Omotosho, all the other four voltage violated load buses are radial extension of the network; they have no alternate routes beside the single connecting transmission.

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