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VOLTAGE MAGNITUDE IMPROVEMENT: A CASE STUDY OF NIGERIAN 330kV TRANSMISSION SYSTEM

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ABSTRACT

Voltage magnitude improvement on power system is important for effective power delivery to consumers. In this study, voltage magnitudes of buses on Nigerian 330kV Transmission System were determined using the Newton-Raphson Power Flow solution method. Buses with low voltage magnitudes were identified. Appropriate shunt capacitor bank ratings in Mega-Volts Ampere (MVA) were determined and installed on the buses with voltage magnitudes that violate limits. It was discovered that the the injection of appropriate MVAr ratings on the buses improved the bus voltage magnitude to fall within acceptable range. Power system losses on the Nigerian 330kV Transmission System were also considerably reduced.

Keywords: Power System, Power Flow Analysis, Voltage Profile, Newton-Raphson, Shunt Capacitor.

1.0. Introduction

The electrical utility is probably the largest and most complex industry in the world (Glover, Sarma and Overby, 2010). It is desirable that voltage at different buses in a power system is equal to the nominal value (i.e. 1pu) at all times. Many phenomenon tend to make the actual voltage differ from the nominal value. An unacceptable level of voltage means voltage instability (Gupta, 2006). The electrical energy is normally generated at the power station far away from the urban areas, where consumers are located and delivered through a network of transmission and distribution. For satisfactory operation of loads on power system, it is desirable that voltage is maintained constant on the power system (Gupta, 2004).

To control the voltage magnitude of an interconnected power system, buses with generators are usually made voltage controlled buses (PV buses). Load Flow solution then gives the voltage levels at the load buses. If some of the load buses voltages work out to be less than the specified lower voltage limit, it is indicative of the fact that the reactive power flow capacity of transmission lines for specified voltage limits cannot meet the reactive load demand (Kothari and Nagrath, 2008). The following means are used to control system reactive power flow: (Glover, et al., 2010)

(i) Prime mover and excitation control of generators

(ii) Switching of shunt capacitor banks, shunt reactors and static VAR system

(iii) Control tap-changing and regulating transformers.

The transmission grid system in Nigeria is predominantly characterized by radial, fragile and very long transmission lines, some of which risk total or partial system collapse (Onohaebi and Igbinovia, 2008). The objective of this research work is to analyze the voltage profiles of buses on the power system with a view to improving voltage magnitudes on buses that do not fall within acceptable voltage limits by the injection of appropriate reactive power (MVAr) on the buses with the aid of shunt capacitor bank connection at the buses.

2.0. Materials and Methods

The Nigerian 24-Bus 330kV Transmission system considered in this work is shown in Figure 1. The total generating capacity of the Power Holding Company of Nigeria (PHCN) is 6200MW of which 1920MW is hydro and 4280MW is thermal (mainly gas fired). The Nigerian 24-Bus 330kV National Grid considered has a total of seven (7) generating stations, seventeen (17) transmission station (totaling 24 buses) and thirty-nine (39) transmission lines (Tijani, 2002).

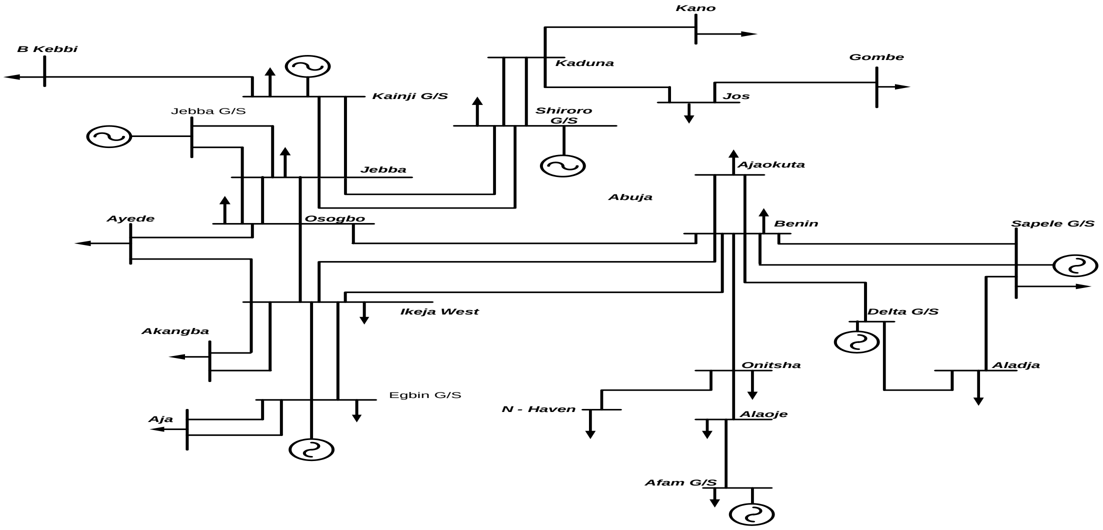

Figure 1: Nigerian 24 Bus 330kV National Grid (Adepoju et al, 2011)

2.1. Load Flow Analysis

The Load Flow Analysis in power system parlance is the steady-state solution of the power system network. In this analysis, the power system network is modeled as an electric network and solved for the steady-state powers, voltages at various buses and hence power at the slack bus, power flow through interconnecting power channels (Kumar and Nagaraju, 2007). Among the Numerous solution methods available for load flow analysis, Newton-Raphson solution method is considered to be the most important because of its convergence characteristics (Kumar and Nagaraju, 2007; Adepoju et al, 2011).

Consider a typical bus of a power system network as shown in Figure 2. Transmission lines are represented by their equivalent π models where impedances have been converted to per – unit admittances on a common MVA base.

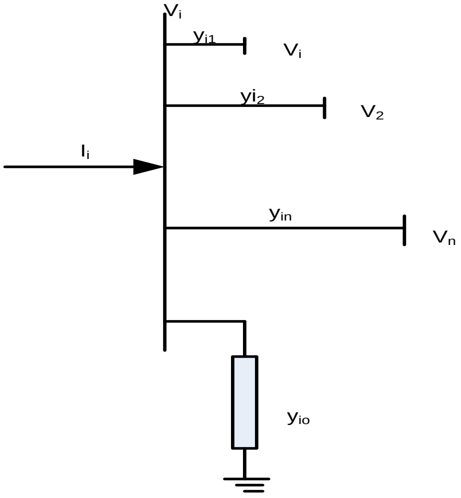

Figure 2: Typical bus of power system (Saadat, 2006)

The non-linear algebraic power flow equation resulting from application of Kirchof's current law to Figure 1 is as follows.

$$I_i = \frac{P_i - jQ_i}{V_i^*} = V_i \sum\nolimits_{i=0}^{n} y_{ij} - \sum\nolimits_{i=1}^{n} y_{ij} V_j \qquad 1$$

Expressing this equation in polar form, we have;

$$I_i = \sum\nolimits^{n}_{j=1} |Y_{ij}|\ |V_j| <(\Theta_{ij} + \delta_j) \qquad 2$$

The complex power at bus is;

$$P_i - jQ_i = V_i^* I_i \qquad 3$$

Substituting from (2) for I$_i$ in (3)

$$P_i - jQ_i = |V_i| < -\delta_i \sum\nolimits^{n}_{j=1} |Y_{ij}|\ |V_j| < \delta_{ij} + \delta_j \qquad 4$$

Separating the real and imaginary parts

$$P_i = \sum\nolimits^{n}_{j=1} |V_i|\ |V_j|\ |Y_{ij}| \cos(\Theta_{ij} - \delta_i + \delta_j) \qquad 5$$

$$Q_i = -\sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| \sin(\Theta_{ij} - \delta_i + \delta_j) \qquad 6$$

Expanding (5) and (6) in Taylor's series about the initial estimate and neglecting all higher order terms results in a set of linear equations.

These equations after linearization can be written in matrix form as.

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \begin{pmatrix} J_1 & J_2 \\ J_3 & J_4 \end{pmatrix} \begin{pmatrix} \Delta \delta \\ \Delta |V| \end{pmatrix} \qquad 7$$

Where element J_1, J_2, J_3, J_4 are elements of Jacobian matrix.

In obtaining the power flow solution by Newton method, consider equation (7)

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \begin{pmatrix} J_1 & J_2 \\ J_3 & J_4 \end{pmatrix} \begin{pmatrix} \Delta \delta \\ \Delta |V| \end{pmatrix}$$

For voltage controlled buses, the magnitudes are known. Therefore, if m buses of the system voltage controlled, m equation involving ΔQ and ΔV and the corresponding column of the Jacobian matrix are eliminated. Accordingly, there are n-1-m reactive power constraints, and the Jacobian matrix is of order (2n-2-m) x (2n – 2 - m). J_1 is of the order (n - 1) x (n - 1), J_2 is of the order (n – 1) x (n- 1 – m), J_3 is of the order (n- 1 - m) x (n -1), and J_4 is of the order (n – 1 - m) x (n – 1- m).

The term $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are the difference between the scheduled and calculated values, known as the power residuals given by

$$\Delta P_i^{(k)} = P^{sch} - P_i^{(k)} \qquad 8$$

$$\Delta Q_i^{(k)} = Q^{sch} - Q_i^{(k)} \qquad 9$$

The new estimates for bus voltages are

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \qquad 10$$

$$|V_i^{(k+1)}| = |V_i^{k}| + \Delta |V_i^{(k)}| \qquad 11$$

2.2. Shunt Capacitor

$$\text{Short Circuit MVA at the bus} = \frac{\text{Base MVA}}{\text{Total reactance of transmission line connecting the bus}} \qquad 15$$

$$\frac{\Delta Q}{\Delta V} = \frac{SCMVA}{\text{Bus Voltage}} \qquad 16$$

$$\Delta Q = \frac{SCMVA}{\text{Bus Voltage}} \Delta V \qquad 17$$

Where

SCMVA = Short Circuit Megavolts Ampere

ΔQ = MVAr Capacity of the Capacitor Bank

ΔV = Voltage Fluctuation

The fact that positive reactive power (VAr) injection at any bus of an interconnected power system would help raise the voltage value at the bus is demonstrated with Figures 3 (Kothari and Nagrath, 2008; Glover, Sarma and Overby, 2010).

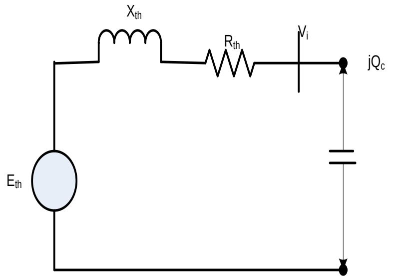

Figure 3: Thevenin Equivalent Circuit showing Reactive Power Injection

Figure 3 shows the Thevenin equivalent circuit of the power system as seen from ith bus. Obviously, $E_{th} = V_i$. If jQ_c from the shunt capacitor is now injected, the following equations are derived.

$$|\Delta V| = |E_{th}| - |V_i'| = -\frac{X_{th}}{|V'|} Q_c \qquad 12$$

Or

$$|V_i'| = |E_{th}| + \left[\frac{X_{th}}{|V_i'|}\right] Q_c = |V_i| + \left[\frac{X_{th}}{|V_i'|}\right] Q_c \qquad 13$$

Since a voltage rise of a few per cent is considered, $|V_i'|$ can further be approximated as

$$|V_i'| = |V_i| + \left[\frac{X_{th}}{|V_i|}\right] Q_c \qquad 14$$

Thus the VAr injection of + jQ_c by the shunt capacitor causes the voltage at the ith bus to rise approximately by $\left[\frac{X_{th}}{|V_i|}\right] Q_c$.

The values of reactive capacitor (+jQ_c in MVAr) to be injected on buses with low voltage magnitudes are given as follows: (Gupta, 2006).

3.0. Results and Discussion

The power flow analysis was carried out using the Newton-Raphson load flow method. The analysis determines the voltage magnitudes, angles in degrees, real and reactive powers on both the generator and load buses on the Nigerian 24-Bus Transmission Grid. The result is shown in Table 1.

It can be observed from Table 1 that the voltage magnitudes and the angle from the load flow solution of Nigerian 330kV system are within the acceptable tolerance range of ± 10 % except voltage magnitudes on buses 16 and 22 (Gombe and Kano) which have magnitudes below ± 10 %. The reason for the low voltage on these two buses is due to their distance from generating stations.

Shunt capacitor banks are then installed on these buses identified to have low voltages in order to inject positive reactive powers on the buses thereby improving the voltage magnitudes on the buses to fall within the acceptable range.

Table 1: Power Flow Solution by Newton-Raphson Method on Nigerian 24 Bus, 330kV System

Bus No.	Bus Name	Voltage Magnitude (pu)	Angles (degrees)	Load Active MW	Reactive MVAr	Generation Active MW	Reactive MVAr
1	EGBIN	1.050	0.00	68.9	51.7	1490.5	769.2
2	DELTA	1.050	-1.14	0.0	0.0	670.0	3.0
3	AJA	1.045	-0.28	274.4	205.8	0.0	0.0
4	AKANGBA	0.988	-5.64	344.7	258.5	0.0	0.0
5	IKEJA-WEST	1.016	-5.19	633.2	474.0	0.0	0.0
6	AJAOKUTA	1.054	-7.00	13.8	10.0	0.0	0.0
7	ALADJA	1.046	-2.71	96.5	72.4	0.0	0.0
8	BENNIN	1.034	-6.63	383.3	287.5	0.0	0.0
9	AYEDE	0.974	-7.79	275.8	206.8	0.0	0.0
10	OSHOGBO	1.026	-4.93	201.2	150.0	0.0	0.0
11	AFAM	1.050	-17.27	52.5	39.4	431.0	464.9
12	ALAOJI	1.030	-17.89	427.0	320.2	0.0	0.0
13	NEW-HAVEN	0.929	-18.89	177.9	133.4	0.0	0.0
14	ONITSHA	0.971	-16.09	184.6	138.4	0.0	0.0
15	BIRNIN-KEBBI	1.010	-3.97	114.5	85.9	0.0	0.0
16	**GOMBE**	**0.866**	**-31.67**	**130.6**	**97.9**	**0.0**	**0.0**
17	JEBBA	1.050	-1.61	11.0	8.2	0.0	0.0
18	JEBBAG	1.050	-1.35	0.0	0.0	495.0	-58.4
19	JOS	0.948	-24.01	70.3	52.7	0.0	0.0
20	KADUNA	0.999	-16.67	193.8	144.7	0.0	0.0
21	KAINJI	1.050	1.55	7.0	5.2	624.7	-114.6
22	**KANO**	**0.880**	**-24.88**	**199.8**	**149.9**	**0.0**	**0.0**
23	SHIRORO	1.050	-12.22	320.1	256.1	388.9	548.1
24	SAPELE	1.050	-5.12	20.6	15.4	190.3	213.4
Total				4200.7	3166.2	4290.4	1825.6

Using equations (150, (16) and (17), a capacitor of 12.65MVAr rating is connected to bus 16 (Gombe). Using the same mathematical method, the MVAr ratings of the capacitor bank to be injected into bus 22 is given as 19.04MVAr. These values are injected and a load flow is carried out again on the Nigerian power system. The results after the injections of appropriate MVAr into the buses where the voltages are found to be low is shown in Table 2. Table 3 shows the power loses (both real and reactive) on the power system before various MVArs were injected and after MVArs have been injected on the power systems.

Table 2: Power Flow Solution by Newton-Raphson Method on Nigerian 24 Bus, 330kV System with Capacitor Banks connected

Bus No.	Bus Name	Voltage Magnitude (pu)	Angles (degrees)	Load		Generation		Injected MVArs
				Active MW	Reactive MVAr	Active MW	Reactive MVAr	
1	EGBIN	1.050	0.00	68.9	51.7	1490.5	769.2	-
2	DELTA	1.050	-1.14	0.0	0.0	670.0	3.0	-
3	AJA	1.045	-0.28	274.4	205.8	0.0	0.0	-
4	AKANGBA	0.988	-5.64	344.7	258.5	0.0	0.0	-
5	IKEJA-WEST	1.016	-5.19	633.2	474.0	0.0	0.0	-
6	AJAOKUTA	1.054	-7.00	13.8	10.0	0.0	0.0	-
7	ALADJA	1.046	-2.71	96.5	72.4	0.0	0.0	-
8	BENNIN	1.034	-6.63	383.3	287.5	0.0	0.0	-
9	AYEDE	0.974	-7.79	275.8	206.8	0.0	0.0	-
10	OSHOGBO	1.026	-4.93	201.2	150.0	0.0	0.0	-
11	AFAM	1.050	-17.27	52.5	39.4	431.0	464.9	-
12	ALAOJI	1.030	-17.89	427.0	320.2	0.0	0.0	-
13	NEW-HAVEN	0.929	-18.89	177.9	133.4	0.0	0.0	-
14	ONITSHA	0.971	-16.09	184.6	138.4	0.0	0.0	-
15	BIRNIN-KEBBI	1.010	-3.97	114.5	85.9	0.0	0.0	-
16	**GOMBE**	**1.081**	**-31.67**	**130.6**	**97.0**	**0.0**	**0.0**	**12.65**
17	JEBBA	1.050	-1.61	11.0	8.2	0.0	0.0	-
18	JEBBAG	1.050	-1.35	0.0	0.0	495.0	-58.4	-
19	JOS	0.948	-24.01	70.3	52.7	0.0	0.0	-
20	KADUNA	0.999	-16.67	193.8	144.7	0.0	0.0	-
21	KAINJI	1.050	1.55	7.0	5.2	624.7	-114.6	-
22	**KANO**	**1.091**	**-24.88**	**199.8**	**149.9**	**0.0**	**0.0**	**19.04**
23	SHIRORO	1.050	-12.22	320.1	256.1	388.9	548.1	-
24	SAPELE	1.050	-5.12	20.6	15.4	190.3	213.4	-
Total				4200.7	3166.2	4290.4	1825.6	-

Table 3: Power Loses on the Nigerian Power System

Bus No.	Bus Name	Power Loses before MVAr Injection		Power Loses after MVAr Injection	
		Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)
16	Gombe	89.682	-1340.333	86.401	-1418.862
22	Kano	89.682	-1340.333	84.332	-1412.199

It can be observed that the voltage magnitudes of buses 16 and 22 have been raised to fall within ± 10 % range of bus voltages nominal values. It can also be observed that power losses on the power system have been reduced considerably.

Conclusion

Voltage profile on power system is very important to the operation of power system and keeping the voltage values within acceptable nominal range is a task that system engineers must face headlong. Load flow analysis was carried out on Nigerian 330kV Transmission Grid, it was observed from the results that voltage profile on buses 16 and 22 were violated. Appropriate shunt capacitor banks were connected to these buses to improve the voltage profile. It was observed that the voltage profile on these buses were improved and fall within limits. Power losses on the power system were also reduced due to the shunt capacitor banks installed on the system. It can be concluded that the voltage profiles of the Nigerian 330kV Transmission System can be improved and power system losses reduced by injection of appropriate reactive power into the system.

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