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Voltage profile enhancement through identification of suitable locations for citing static var compensators

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Abstract

This paper presents transmission network expansion for 330 kV, 30-bus Nigerian transmission network. The mathematical models for power flow analysis were formulated using Newton-Ralphson technique to determine the steady state bus voltage magnitude and angle; active and reactive power flows and power losses. Six buses (19, 20, 22, 24, 26 and 27) had their voltage magnitude lower than the statutory limit of 100 ±5%. Static Var Compensator (SVC) was incorporated to the low voltage buses. The modeled equations were modified with SVC and the load flow simulation was repeated. With the SVC, all the bus voltages were within the statutory limit. The active and reactive power loss without the SVC was 219.08 MW and 409.83 MVAr respectively while their values were 185.46 MW and 96.61 MVAr with the SVC. The values of the reactive power given by the SVC at the violated buses were -152.40, -37.0, -93.80, -1.41, -138.05 and -181.78 MVAr respectively. The negative values indicate that SVC would absorbed leading vars or generates negative vars into the network. The percentage improvement in reactive power (76.43%) using the SVC was more than that of active power (15.35%). The simulation also converged faster from 9th to 8th iteration with the SVC.

Keywords: injection of vars, SVC, voltage stability, line loss, transmission expansion, convergence

Introduction

Electric energy can be transmitted over long distances with ease and high efficiency if it is properly designed. Therefore, good efforts in design must be directed toward reliable and quality power supply to achieve high efficiency. As the demand for electric power is increasing on a daily basis, a robust strategic planning for the growth of power system is critical for the future. This necessitate constant expansion planning such as building new resources in the form of generation plants and transmission network to cater for the ever increasing demand of the consumers. The effort of meeting the supply of electricity with the demand of consumers has led to dramatic changes in power system operation and planning.

Power is conveyed from generating station to the consumers via transmission lines. Power is a product of voltage and current. Current is the movement of charges from one location to the other. Moving object always encounter frictional forces which would result losses. The voltage on the other hand is the force behind moving charges and it cannot encounter losses but drops along the transmission line's impedance. To reduce losses and voltage drop on transmission network to the consumers, power is transmitted at high voltage and low current as presented by the author in reference [1]. Despite high voltage transmission and low currents, voltage drop is still high on long and heavily loaded transmission lines.

The major reason of the high voltage drop in power system operation is the insufficient reactive power flow on transmission network as discussed in reference [2]. Authors in reference [3] explain that the strength of any transmission line varies with the load and its length. A weak network is one which cannot be loaded up to its full capacity limit without yielding a lower power transfer capability as discussed in references [4, 5]. Most connected loads on power system are inductive, they demand lagging reactive power. Reactive power is needed to maintain the voltage to deliver the real power. The conventional method of supplying reactive power is to overexcite the generator. The lagging reactive power generated by the overexcited generators is not enough for a complex power system. Generator's reactive power cannot handle the reactive power needed by heavy loaded transmission lines. High voltage drop would occur on such lines due to high current demanded by the load. In this wise, wattles power must be provided to compensate for insufficient reactive power. For short and moderately loaded transmission lines, the reactive power can be controlled by varying the excitation of the generator. But for long transmission lines, variation of the excitation of the generator cannot meet the required reactive power. High voltage drop would take place due to high impedance of the long transmission line. High voltage drop is objectionable in power system operation since the basic function of any electric power system is to convey electricity reliably and at a well synchronized frequency and voltage according to authors in reference [6].

In this paper, efforts are concentrated towards voltage compensation on the transmission lines. Since the power demand is dynamic, the transmission network design must be also dynamic to improve on the voltage stability. The incorporation of voltage compensator serves as the reinforcement of an existing power transmission network to enhance the performance of the power network and to cater for the ever-increasing demand of power. This could be seen as the expansion of the transmission network. Transmission expansion planning, as discussed by authors in reference [7], involves determination of optimal placement of new transmission facilities to be installed so that they will operate in an optimal manner with regards to technical constraints. Voltage drop on the transmission network could be assessed by reactive power requirement in the network. The reactive compensators that could be used in power system are synchronous condenser, static capacitor/static var compensator, shunt reactor, series capacitor, parallel transmission line and tap changing transformer.

A synchronous condenser can supply reactive compensation equal to its rating and absorb up to 50% of its capacity. Author in reference [8] revealed that the power loss in synchronous condenser is much greater than that in capacitor. However, small size synchronous condensers are very uneconomical. As such the synchronous condensers have to be installed at one point only. However, failure of a synchronous condenser means loss of total condenser capacity. Synchronous condenser adds to the short circuit currents in the system and increase the circuit breaker ratings. The voltage profile of Nigerian power system, used in this paper as case study, varies from bus to bus with many bus voltages less than the statutory value. This type of compensator is not recommended for Nigeria power system network because compensators are needed in many buses rather than being installed at one point.

Static capacitor installations can be distributed in the system as discussed in reference [8] more effectively. This is used for lagging power factor. They are connected either directly to a bus bar or the tertiary winding of a 3-winding transformer, near the load terminals, in factory substations, switching substation etc.to produce leading reactive compensation and thus to reduce line current and total KVA loading of the substation transformer. It is documented in reference [8] that by using shunt capacitors, line voltage drop is reduced and the voltage regulation is improved. Shunt capacitors are switched in when KVA demand on the distribution system rises and voltage of the bus drops. The ratings of a static capacitor bank can be changed very easily as per requirement. Capacitors units can be added to the bank or taken away from it easily. A failure of one unit of capacitor bank affects that unit only. The remaining units continue to do their jobs. This type of compensator could be used for Nigeria power network.

The maximum power that can be transferred on a transmission line to achieve voltage stability is directly proportional to the product of the sending and the receiving end voltages and inversely proportional to the line reactance between them. Static capacitor could be used to increase the receiving end voltage.

Series capacitors are connected in series with the conductor to reduce the inductive reactance between the source and the load. They are employed when the voltage drop is the limiting factor and total line reactance is high. They are however, used in extra high voltage EHV (300 kV) and ultra-high voltage UHV (400 kV) transmission lines and are most economical for transmission distance over 350 km as documented in reference [9]. High over voltage is produced across the capacitor terminal under short circuit conditions and the drop across the capacitor under faulty condition may be as large as twenty times that caused by full load current under certain conditions. The transmission network of Nigeria power system is operating between 132 kV and 330 kV. This type of compensator is not appropriate for Nigeria power system due to voltage range, high current during fault condition and transmission distance.

Shunt reactors are widely used to reduce high voltages under light loads condition. For Nigeria power system network used as a case study, the load on the system is heavy load. Therefore, this method is not applicable.

Materials and Methods

The static simultaneous non-linear power flow equations given by Newton-Raphson iterative method is

$$P_i = \sum_{k=1}^{N} |V_i||V_k|\left[G_{ik}\cos(\delta_i - \delta_k) + B_{ik}\sin(\delta_i - \delta_k)\right] \qquad (1)$$

$$Q_i = \sum_{k=1}^{N} |V_i||V_k|\left[G_{ik}\sin(\delta_i - \delta_k) - B_{ik}\cos(\delta_i - \delta_k)\right] \qquad (2)$$

Modelling SVC

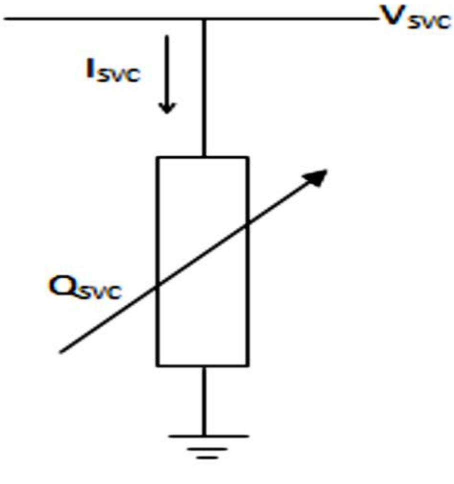

Fig 1: Equivalent circuit of the SVC

When SVC is applied to the violated bus which serves as receiving end or load bus as shown in Figure1, the active and reactive power flow equations are modified and are given by eqns (3) and (4) respectively as presented by the author of reference [9].

$$P_i = \sqrt{\frac{Q_{SVC} X_L X_C}{X_C - X_L}} \sum_{i=1}^{n} Y_{ij} V_i \cos\left(\theta_{ij} + \delta_i - \delta_j\right) \qquad (3)$$

$$Q_i = \sqrt{\frac{Q_{SVC} X_L X_C}{X_C - X_L}} \sum_{i=1}^{n} Y_{ij} V_i \sin\left(\theta_{ij} + \delta_i - \delta_j\right) \qquad (4)$$

Where,
Q_{SVC} is the MVAR of the SVC, X_L is the inductive reactance of the SVC, X_C is the capacitive reactance of the SVC, Y_{ij} is the admittance of the transmission line connecting the buses under consideration, V_j is the voltage magnitude of the bus, θ_{ij} is the voltage angle and δ is the load angle.
(SVC) provides either capacitive or inductive injected voltage compensation. It acts as capacitor once power flow through the line is increased and as an inductor whenever power flow needs to decrease. In its operation, SVC acts as resistor when capacitor is charging by d,c and as generator while discharging as discussed by the authors of reference [10].
When the SVC (compensator) is connected to the load bus that is experiencing low voltage, the power transfer for steady state stability condition on the transmission line is modelled as shown in Figure 2.

Fig 2: Power transfer modelling

Where,
$E_g < \delta_g$ is the generator/sending end and $E_m < \delta_m$ is the load/motor or receiving end, P_{gm} and Q_{gm} are the active and reactive power flow on the line between the compensated bus and the adjacent bus that is not violated [8]

$$P_{gm} = \frac{E_g E_m}{X} \sin \delta_{gm} \qquad (5)$$

$$Q_{gm} = \left[\frac{E_g^2}{X} - \frac{E_g E_m}{X} \cos \delta_{gm}\right] \qquad (6)$$

Where $\delta_{gm} = \delta_g - \delta_m$
Since E_m would have been increase by the SVC compensator, the angle δ_m will be reduced and δ_{gm} will increase. Therefore, $\sin\delta_{gm}$ will increase and $\cos\delta_{gm}$ will reduce. Hence, the active and reactive power flow will increase.

Data for the Sample Network

Table 1: Generation Data

Bus No	Voltage Mag.	Generation MW	Bus No	Voltage Mag.	Generation MW
1	1.05	0	7	1.05	190.3
2	1.05	670	8	1.05	750
3	1.05	431	9	1.05	750
4	1.05	495	29	1.05	410
5	1.05	624.7	30	1.05	342.10
6	1.05	388.9			

Table 2: Load Data

Bus No	Load		Bus No	Load		Bus No	Load	
	MW	MVar		MW	Mvar		MW	Mvar
10	274.4	205.8	17	201.2	150.9	24	70.3	52.7
11	344.7	258.5	18	427	320.2	25	193	144.7
12	633.2	474.9	19	177.9	133.4	26	220.6	142.9
13	13.8	10.3	20	184.6	138.4	27	110	89
14	96.5	72.4	21	114.5	85.9	28	290.1	145

15	383.3	287.5	22	130.6	97.9			
16	275.8	206.8	23	11.3	8.2			

Results and Discussion

Table 3 shows the load flow result for the sample network using Neplan application software. The results display voltage magnitude and angle at every bus of the system. Six of the buses (Calabar, Gombe, Jos, Kano, New haven and Onitsha) had voltage magnitude less than the statutory limit of 100 ±5 % of nominal voltage. Their voltage magnitudes are 93.19%, 66.08 %, 81.41 %, 81.38 %, 90.02% and 94.66% respectively. Those buses are indicated with red colour in Table 3. The total active and reactive power losses are 219.08 MW and 409.83 MVAr respectively.

Table 3: Load Flow Result without SVC

BUS NO	VOLTAGE (%)	ANGLE (degree)	P LOAD	Q LOAD	P GEN	Q GEN
1	105.00	0.00	529.72	51.70	0.00	745.58
2	105.00	16.10	0.00	0.00	670.00	23.42
3	105.00	28.60	52.50	39.40	431.00	845.55
4	105.00	10.10	0.00	0.00	495.00	54.49
5	105.00	13.00	7.00	23.17	624.70	0.00
6	105.00	-2.30	70.30	36.10	388.90	834.24
7	105.00	11.90	20.60	15.40	190.30	332.81
8	105.00	73.60	0.00	0.00	750.00	249.83
9	105.00	6.20	0.00	0.00	750.00	164.17
10	104.49	-0.30	274.40	205.80	0.00	0.00
11	101.16	3.70	344.70	258.50	0.00	0.00
12	101.91	4.10	633.20	474.90	0.00	0.00
13	104.28	10.60	13.80	10.30	0.00	0.00
14	104.50	14.40	96.50	72.40	0.00	0.00
15	103.47	10.90	383.30	287.50	0.00	0.00
16	100.41	4.60	275.80	206.80	0.00	0.00
17	102.68	7.20	201.20	150.90	0.00	0.00
18	101.96	28.10	427.00	320.20	0.00	0.00
19	90.02	11.70	177.90	133.40	0.00	0.00
20	94.66	14.60	184.60	138.40	0.00	0.00
21	97.78	7.50	114.50	85.90	0.00	0.00
22	66.08	-26.70	130.60	97.90	0.00	0.00
23	104.90	9.90	11.30	8.20	0.00	0.00
24	81.41	-15.30	70.30	52.70	0.00	0.00
25	96.03	-7.00	193.00	144.70	0.00	0.00
26	81.38	-17.20	220.60	142.90	0.00	0.00
27	93.19	48.10	110.00	89.00	0.00	0.00
28	102.66	-4.40	290.10	145.00	0.00	0.00
29	105.00	10.10	0.00	0.00	410.00	194.90
30	103.74	6.60	0.00	0.00	342.10	156.00

Table 4 is the power flow results for the network with the incorporation of SVC to the constraint buses. The simulation converged at the eighth (8) iteration while the uncompensated network converged at the ninth iteration. The network with SVC has the advantage of faster convergence. With the application of SVC, all the bus voltage magnitudes were within the statutory limits. The total active power loss with SVC was 185.46 MW while the loss was 219.08 MW without the SVC. This is a reduction of 15.35%. Likewise, the reactive power loss was reduced from 409.83 MVAr to 96.61 MVAr representing 76.43%. The values of the reactive power given by the SVC at the violated buses (19, 20, 22, 24, 26 and 27) were -152.40, -37.0, -93.80, -1.41, -138.05 and -181.78 MVAr respectively. The MVAr values of the SVC are all negative which shows that it generates negative var into the network or absorbs positive var from the network.

Table 4: Load Flow Result with (SVC)

BUS NO	VOLTAGE (%)	ANGLE	P LOAD	Q LOAD	P GEN	Q GEN	Q SHUNT
1	105.00	0.00	563.34	51.70	0.00	750.80	0.00
2	105.00	16.40	0.00	0.00	670.00	10.93	0.00
3	105.00	28.40	52.50	39.40	431.00	609.54	0.00
4	105.00	10.80	0.00	0.00	495.00	49.39	0.00
5	105.00	13.70	7.00	23.60	624.70	0.00	0.00
6	105.00	-1.30	70.30	36.10	388.90	396.42	0.00
7	105.00	12.20	20.60	15.40	190.30	252.03	0.00

8	105.00	70.30	0.00	0.00	750.00	124.22	0.00
9	105.00	6.40	0.00	0.00	750.00	161.72	0.00
10	104.49	-0.30	274.40	205.80	0.00	0.00	0.00
11	101.17	3.80	344.70	258.50	0.00	0.00	0.00
12	101.92	4.30	633.20	474.90	0.00	0.00	0.00
13	104.67	10.90	13.80	10.30	0.00	0.00	0.00
14	104.50	14.80	96.50	72.40	0.00	0.00	0.00
15	103.85	11.20	383.30	287.50	0.00	0.00	0.00
16	100.43	4.80	275.80	206.80	0.00	0.00	0.00
17	102.71	7.70	201.20	150.90	0.00	0.00	0.00
18	102.80	27.90	427.00	320.20	0.00	0.00	0.00
19	100.00	11.90	177.90	133.40	0.00	0.00	-152.40
20	100.00	14.70	184.60	138.40	0.00	0.00	-37.02
21	97.78	8.20	114.50	85.90	0.00	0.00	0.00
22	100.00	-19.70	130.60	97.90	0.00	0.00	-93.80
23	104.91	10.50	11.30	8.20	0.00	0.00	0.00
24	100.00	-12.90	70.30	52.70	0.00	0.00	-1.41
25	101.91	-5.90	193.00	144.70	0.00	0.00	0.00
26	100.00	-14.50	220.60	142.90	0.00	0.00	-138.05
27	100.00	46.00	110.00	89.00	0.00	0.00	-181.78
28	102.66	-3.30	290.10	145.00	0.00	0.00	0.00
29	105.00	10.30	0.00	0.00	410.00	172.71	0.00
30	103.76	6.80	0.00	0.00	342.10	156.00	0.00

Conclusion

This paper presents transmission network expansion using SVC to achieve voltage stability improvement for six buses which have voltage magnitude lesser than the statutory limit in 330 kV, 30-bus, Nigerian power system. Neplan application software is used for the analysis. Both active and reactive powers are improved with the usage of SVC for the sample network. The active power is improved by 15.35% while the reactive power is improved by 76.43%. The incorporation of SVC also reduced simulation time from nine iterations to eight iterations. The MVAR values of the SVC are all negative which shows that it generates negative var into the network or absorbs positive var from the network.

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