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Power Flow Control Analysis of Transmission Line Using Static VAr Compensator (SVC)

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***Abstract**:Control of reactive power and voltage constitute part of the major challenge in the power system industry. Adequate absorption or injection of reactive power into electric power transmission systems solves power quality problems like voltage profile maintenance at all power transmission levels, transmission efficiency and system stability. Globally, there is increasing demand for electricity to feed the technology-driven economy, while the commensurate expansion of power generation and transmission to meet up with such demand has been severely limited due to inadequate resources and environmental factors. Flexible AC Transmission System (FACTS) controllers, such as the Static VAr Compensator (SVC), employ latest technology in the design of power electronic switching devices for electric power transmission systems to control voltage and power flow, and improve voltage regulation without the need to expand the power generation and transmission facilities. In this work, the capability of SVC in stabilizing power system's voltage through reactive power compensation was investigated. Power flow equations involving voltage drop with/without SVC were developed. Modeling equations for SVC were also developed and used to determine its parameters. The Nigeria 330kV network, 28-bus power system used for the study was modeled using MATLAB/SIMULINK software. From the simulations, the compensated and uncompensated voltages at each of the 28 buses were evaluated. It was observed from the analysis that some buses in the network had very weak voltage profile consequent to either excessive generation or absorption of the reactive power at such buses. It is therefore pertinent to note that not all the buses within the network need voltage compensation and as such, only buses with very weak voltage profile require the incorporation of SVC. Hence it can be concluded that in order to enhance the transmission system performance of the Nigerian 330kV power system, the control of the voltages at certain buses through the application of SVC is required.*

***Keywords**: Facts, Svc, Transmission Line Analysis, Reactive Power Control, 28-bus*

I. Introduction

Globally, there is increasing demand for electricity to feed the technology-driven economy, while the commensurate expansion of power generation facilities and transmission lines to meet up with such demand has been severely limited due to inadequate resources and environmental factors. In power system network voltage control, reactive power is both the challenge and the solution. It is, therefore, important that a balance of reactive power be obtained in the operation of electric power transmission systems because the control of voltage can be lost if this is not achieved. Adequate reactive power regulation of electric transmission networks can solve power quality problems by improving the power system voltage profile, transient stability improvement, increase in power transfer capacity and minimization of transmission line loss. FACTS controllers, such as the Static VAr Compensator (SVC), employ latest technology in the design of power electronic switching devices. These devices are used to control the voltage and power flow in a transmission system to improve voltage regulation without the need to expand the power generation and transmission facilities. By dynamically providing reactive power, SVC can be used for voltage regulation and compensation, transient stability improvement, power system oscillation damping improvement, increase in power transfer capacity and minimization of transmission line loss.

II. Background To The Study

The ability to control power flow in an electric power transmission system without generation rescheduling or topology changes can improve the power system performance. Using controllable components, the line flows can be changed in such a way that thermal limits are not exceeded, stability margin increased, in addition to increase in power transfer capacity and minimization of transmission line loss without violating the economic generation dispatch. FACTS technology is the ultimate tool for getting the most out of existing power system infrastructures through rapid regulation of the system's reactive power. Ali [1] investigated the performance of Static Synchronous Compensators (STATCOM) and SVC on voltage stability in power system. In the study, MATLAB/SIMULINK software simulations showed that STATCOM is more effective in midpoint voltage regulation on transmission line. Comparison between STATCOM and SVC under fault condition was also simulated and the result showed that STATCOM has the capacity to provide more reactive power for the period of a fault than SVC. The response time of STATCOM was faster than that of SVC. In the work by Murali [2], simulation and comparison of various FACTS devices using PSPICE software have been done. How to improve steady state stability by placing SVC at different places has been discussed in the study by Bhavin [3]. In the study by Akter [4], MATLAB/SIMULINK software simulation was used to demonstrate the performance of the system for each of the FACTS devices for example, Static VAr compensator (SVC), STATCOM, Thyristor controlled series capacitor (TCSC), Static synchronous series compensator (SSSC) and Unified power flow controller (UPFC) in improving the power profile and thereby voltage stability of same. Using MATLAB/SIMULINK software, performance of Fixed capacitor, shunt Thyristor Controlled Reactor (FC-TCR) and STATCOM has been discussed in the work by Das [5]. Modeling and Simulation of various FACTS devices (FC-TCR, STATCOM, TCSC and UPFC) have been done using MATLAB/SIMULINK software in the work by Dipti [6]. The research by Pardeep [7], discussed how SVC has successfully been applied to control the dynamic performance of transmission system and regulate the system voltage effectively.

III. Methodology

SVC application studies require appropriate power system models and study methods covering the particular problem to be solved by the application. The following studies are normally required for an SVC application from the early planning stage till operation [8].

- Load flow studies.
- Small and large disturbance studies.
- Harmonic studies.
- Electromagnetic transient studies and
- Fault studies.

3.1 Modeling of Static VAr Compensator for Power System Studies

The functional diagram of the SVC in fig.1 shows that one branch of the SVC is purely inductive while the other branch is purely capacitive. Therefore, the SVC consumes no active power. It either injects (capacitive) reactive power to increase the system's voltage or consumes (inductive) reactive power to reduce the system's voltage. Since the reactor consumes reactive power, the (inductive) reactor current (I_L) is positive while the capacitor which injects reactive power into the system, has negative current (I_C).

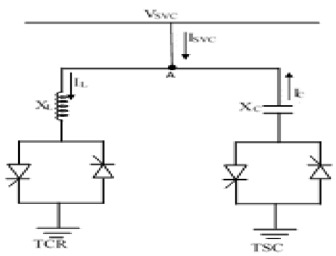

Figure1: Functional diagram of a TCR-TSC SVC

From circuit theory, it is shown that:

$$I_{SVC} + I_C - I_L = 0 \quad (1)$$

Therefore the SVC current (I_{SVC}) at maximum VAr absorption, could be expressed as follows:

Looking at point A and using Kirchoff current law (KCL), we have:

$$I_{SVC} = I_L - I_C \tag{2}$$

$$I_C = \frac{V_{SVC}}{X_C} \tag{3}$$

and

$$I_L = \frac{V_{SVC}}{X_L} \tag{4}$$

where

X_L = Inductive reactance of the SVC

X_C = Capacitive reactance of the SVC

C = Capacitance of the fixed SVC capacitor

L = Inductance of the SVC inductor

V_{SVC} = Magnitude of the bus voltage

On the assumption that no real power is consumed by the SVC (i.e. $P_{SVC} = 0$) then:

$$Q_{SVC} = I_{SVC} \times V_{SVC} \tag{5}$$

Comparing equations (1) and (5):

$$Q_{SVC} = (I_L - I_C) \times V_{SVC} \tag{6}$$

Combining equations (2), (3) and (6), yield equations (7) to (9):

$$Q_{SVC} = \left(\frac{V_{SVC}}{X_L} - \frac{V_{SVC}}{X_C} \right) \times V_{SVC} \tag{7}$$

$$Q_{SVC} = \left(\frac{1}{X_L} - \frac{1}{X_C} \right) \times V_{SVC}^2 \tag{8}$$

$$Q_{SVC} = \left(\frac{X_C - X_L}{X_L X_C} \right) V_{SVC}^2 \tag{9}$$

SVC controllers are designed in such a way that the TCR is switched on when the bus voltage becomes higher than the reference voltage and vice-versa. As a result, when the VAr absorption is at maximum, the TCR become operational and $Ic = 0$. Hence:

$$Q_{SVC}^{\max} = \frac{1}{X_L} V_{SVC}^2 \tag{10}$$

When the VAr absorption is at minimum, $I_L = 0$. Hence:

$$Q_{SVC}^{\min} = -\frac{1}{X_C} V_{SVC}^2 \tag{11}$$

Thus, the bus voltage would be regulated at or near the base voltage.

3.2 Equations for the Bus Voltage and Voltage Drop

Consider an electric power transmission line connecting two buses i and k in any given power system network as represented in Fig. 2.

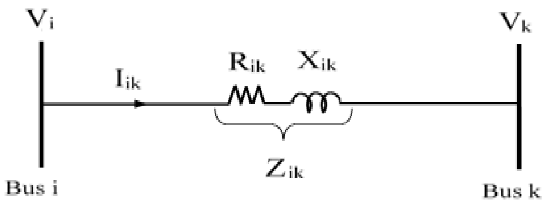

Figure 2: Transmission line model of a power system network

Definition of the symbols used in the configuration of the transmission line model in fig. 2 are as follows:

V_k = Complex voltage at bus k

V_i = complex voltage at bus i

I_{ik} = Complex current flow from bus i to k

R_{ik} = The transmission line resistance between buses i and k

Z_{ik} = The transmission line impedance between buses i and k

X_{ik} = The transmission line reactance between buses i and k

From Fig. 2, the voltage drop (V_d) between buses i and k can be expressed as:

$$V_d = V_i - V_k \tag{12}$$

By applying Ohm's law, the complex current flowing from bus i to k is expressed as:

$$I_{ik} = \frac{V_i - V_k}{Z_{ik}} \tag{13}$$

where

$$Z_{ik} = R_{ik} + X_{ik}$$

Equation (13) is expressed in the admittance form as:

$$I_{ik} = (V_i - V_k)Y_{ik} \tag{14}$$

where

$Y_{ik} = \frac{1}{Z_{ik}}$ and is defined as the admittance of the transmission line.

The complex power (S_{ik}) flowing from bus i to k is given by:

$$S_{ik} = V_i I_{ik}^* \tag{15}$$

Expressing the complex power of equation (15) in real power (P) and reactive (Q) power form yields;

$$S_{ik} = P_{ik} + Q_{ik} = V_i I_{ik}^* \tag{16}$$

Taking the conjugate of the equation (16) yields:

$$P_{ik} - Q_{ik} = V_i^* I_{ik} \tag{17}$$

hence

$$I_{ik} = \frac{P_{ik} - Q_{ik}}{V_i^*} \tag{18}$$

Comparison of equations (12), (13) and (18) gives equation (19) as:

$$\frac{P_{ik} - Q_{ik}}{V_i^*} = V_d Y_{ik} \tag{19}$$

Consequently:

$$V_d = \frac{P_{ik} - Q_{ik}}{V_i^* Y_{ik}} \tag{20}$$

Analysis of equation (20) shows that by adjusting the system's reactive power at bus k while keeping the voltage at bus i constant, the voltage between buses i and k can be controlled and the system's total voltage drop minimized.

Assuming that the SVC is installed at bus k, then equation (12) becomes:

$$V_d = V_i - V_{SVC} \tag{21}$$

Comparing equations (9) and (21) yields:

$$V_d = V_i - \sqrt{\frac{Q_{SVC} X_L X_C}{X_C - X_L}} \tag{22}$$

From equation (21), it can be seen that if the voltage at bus i is kept constant, then by regulating the voltage at bus k at or near the base voltage, the power system's voltage is stabilized and the voltage drop minimized.

IV. Results And Discussion

The test system configuration is based on the Nigerian 330kV, 28-bus power system. The Nigerian Electricity Network comprises 11,000 km transmission lines (330 and 132 kV), 24000 km of sub-transmission line (33 kV), 19,000 km of distribution line (11 kV) and 22,500 substations (National Control Centre, Power Holding Company of Nigeria, 2012). It has only one major loop system involving Benin-Ikeja West-Ayede-Oshogbo and Benin. The absence of loops accounts mainly for the weak and unreliable power system in the country. The single line diagram of the existing 28-bus 330 kV Nigerian transmission network used as the test system is shown in figure 3. It comprises 9 generating stations, 28 buses and 52 transmission lines.

Based on the MATLAB/SIMULINK configuration for this work, simulations were carried out at all the load buses within the 330kV, 28-bus Nigeria power system. Simulations of each load bus in the system without the SVC were done and the system voltage magnitude at each of the load bus were obtained. Conversely, simulations of each load bus in the system with the incorporation of SVC were carried out and the system voltage magnitude at each of the load bus were also obtained. To show the performance of the SVC, the system voltage differential at each of the load bus with/without SVC, were computed.

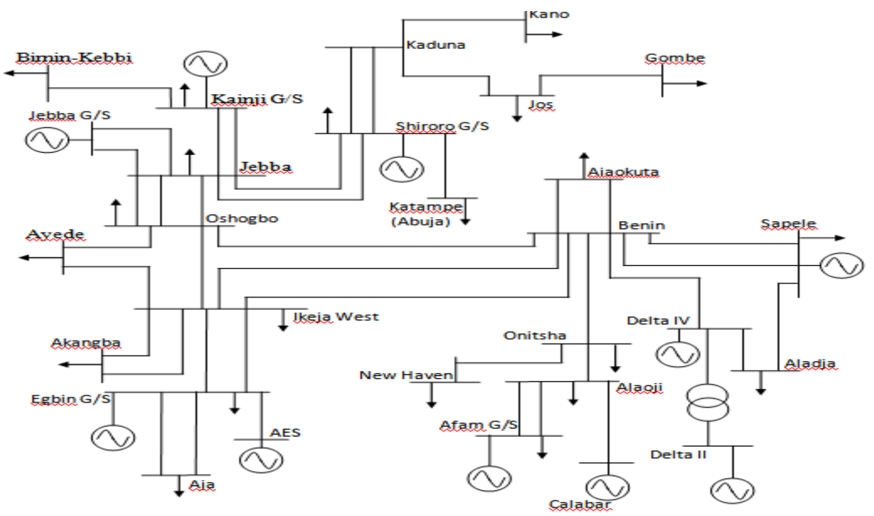

Figure 3: The 330kV, 28-bus Nigerian power system (National Control Centre, Power Holding Company of Nigeria, 2012)

Table 1: The ith and kth bus voltages of the Nigerian 28-bus power system with/without SVC.

Bus		No SVC connected		SVC connected		Performance of SVC	
i	k	$V_i(pu)$	$V_k(pu)$	$V_{i(SVC)}(pu)$	$V_{k(SVC)}(pu$	$V_{i(SVC)} - V_i$	$V_{k(SVC)} - V_k$
1	2	0.3486	0.2548	0.3930	0.2684	0.0444	0.0136
1	3	0.3486	0.3118	0.3930	0.3388	0.0444	0.027
1	23	0.3486	0.6704	0.3930	0.6816	0.0444	0.0112
2	6	0.2548	0.2029	0.2684	0.2462	0.0136	0.0433
2	11	0.2548	0.6853	0.2684	0.6920	0.0136	0.0067
2	17	0.2548	0.6813	0.2684	0.6889	0.0136	0.0076
2	19	0.2548	0.1859	0.2684	0.2799	0.0136	0.094
3	2	0.3118	0.2548	0.3388	0.2684	0.027	0.0136
3	10	0.3118	0.6947	0.3388	0.6981	0.027	0.0034
4	1	0.02133	0.3486	0.02885	0.3930	0.00752	0.0444
4	3	0.02133	0.3118	0.02885	0.3388	0.00752	0.027
5	8	0.1911	0.08298	0.3384	0.2653	0.1473	0.18232
6	20	0.2029	0.1469	0.2462	0.2516	0.0433	0.1047
6	21	0.2029	0.6960	0.2462	0.7027	0.0433	0.0067
7	3	0.3043	0.3118	0.3400	0.3388	0.0357	0.027
10	18	0.6947	0.6686	0.6981	0.6983	0.0034	0.0297
11	15	0.6853	0.2116	0.6920	0.2262	0.0067	0.0146
17	15	0.6813	0.2116	0.6889	0.2262	0.0076	0.0146
21	22	0.6960	0.7004	0.7027	0.7071	0.0067	0.0067

23	25	0.6704	0.6974	0.6816	0.7042	0.0112	0.0068
23	27	0.6704	0.6880	0.6816	0.6947	0.0112	0.0067
25	23	0.6974	0.6704	0.7042	0.6816	0.0068	0.0112
25	26	0.6974	0.2720	0.7042	0.7581	0.0068	0.4861
27	28	0.6880	0.4674	0.6947	0.5367	0.0067	0.0693
28	5	0.4674	0.1911	0.5367	0.3384	0.0693	0.1473
28	16	0.4674	0.2216	0.5367	0.5480	0.0693	0.3264

Table 2: Identified weak buses within the network and their compensated voltage values.

Bus identification		Bus voltage without SVC installed (pu)	Bus voltage with SVC installed (pu)	Bus voltage compensation (pu)
Name	No			
Jos	5	0.1911	0.3384	0.1473
Gombe	8	0.08298	0.2653	0.18232
Kano	16	0.2216	0.5480	0.3264
Ajaokuta	19	0.1859	0.2799	0.094
N-Haven	20	0.1469	0.2516	0.1047
B-Kebbi	26	0.2720	0.7581	0.4861

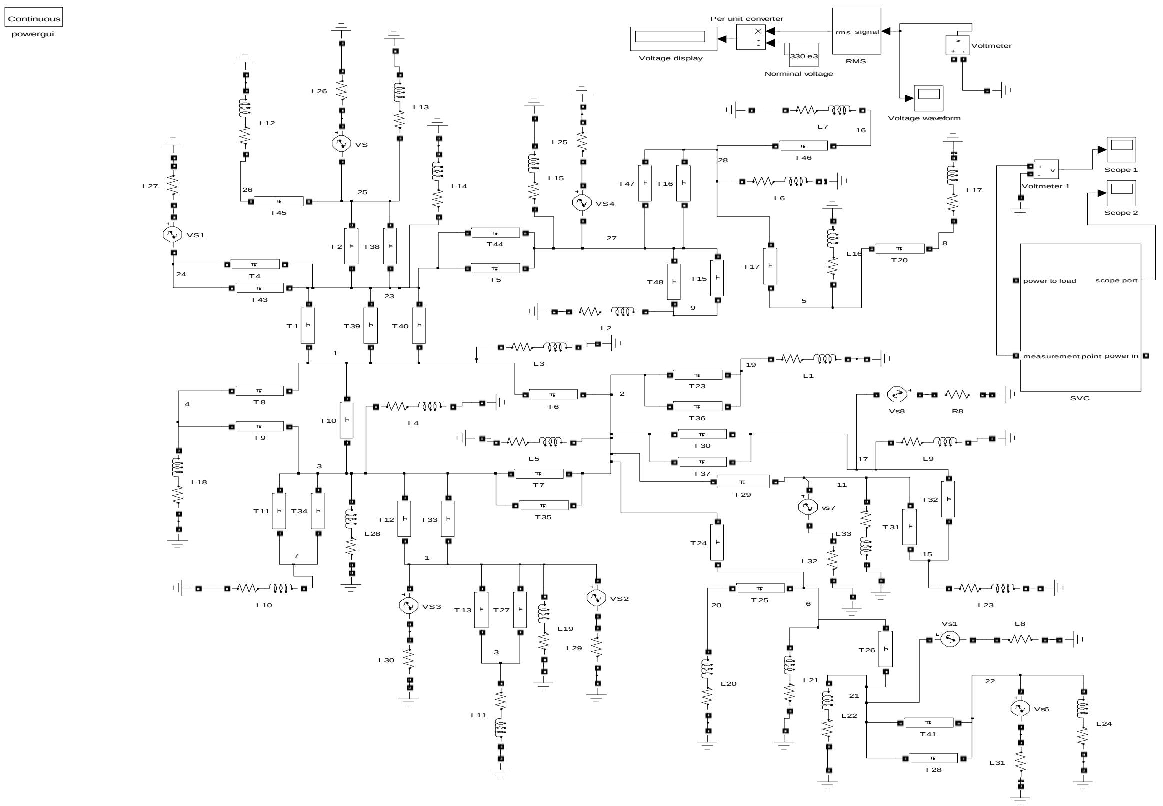

Figure 4: SIMULINK model of the Nigeria 330kV, 28-bus power system

Table 1 is a detailed analysis of the voltages at each of the load bus within the network with/without SVC compensation. It has been observed from this analysis that some buses in the network have very weak voltage profile consequent to either excessive generation or absorption of the reactive power. It is pertinent to note that not all the buses within the network need compensation and as such, only buses with very weak voltage profile require the incorporation of SVC. This information could be very valuable to the power engineers in the installation of SVC in the network. The buses, where compensation with SVC is needed, were identified and depicted in table 2. From the analysis, the overall system voltage compensation with SVC was 10.18%.

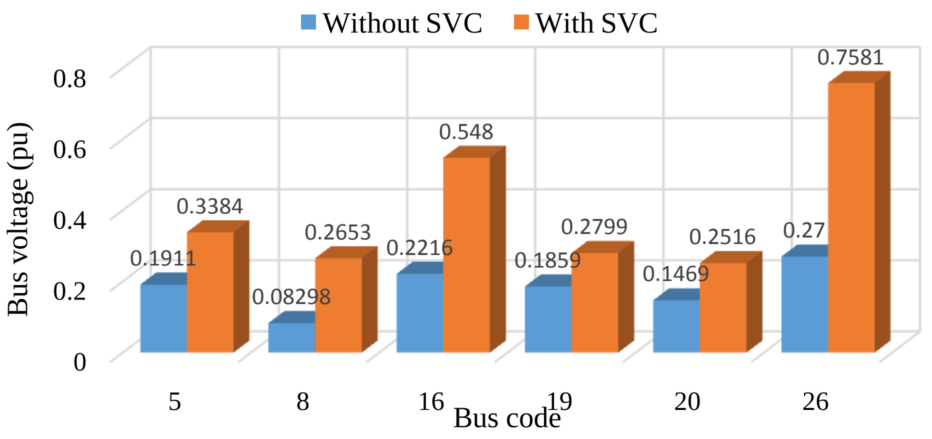

Figure 4: Weak bus voltage compensation representation

V. Conclusion

In this research work, based on the SVC and the power system parameters, SIMULINK blocks have been used to implement the Nigerian 330kV power system network, which comprises 9 generation stations, 28-buses and 52 transmission lines. The simulations were carried out in the MATLAB/ SIMULINK environment. From the simulations, the compensated and uncompensated voltages at each of the 28 buses were evaluated. It was observed from the analysis that some circuits (buses) in the network have very weak voltage profile consequent to either excessive generation or absorption of the reactive power flow at such buses. It is, therefore, pertinent to note that not all the buses within the network need voltage compensation and as such, only buses with very weak voltage profile require the incorporation of SVC. Hence, it can be concluded that in order to enhance the transmission system performance of the Nigerian 330kV power system, the control of the voltages at certain buses through the application of SVC is required. This could be practically implemented on the Nigerian power system network to improve the huge demand for power in the country, because at the moment, only synchronous reactors, which are not as effective as SVC, are being used to control the flow of reactive power in the network.

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