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Minimization of Active Transmission Loss in Power Systems using Static Var Compensator

Matthew Simeon[1], Wara Samuel Tita[2], Adejumobi I.A.[3] and Amuta Elizabeth[4]

[1,2,4] Covenant University, Ota. [3]Federal University of Agriculture, Abeokuta.

Abstract

Increasing demand for electrical power as a result of modern civilization has imposed challenges such as voltage instability, transmission loss, and power factor fluctuations on power systems. In an attempt to overcome these challenges, FACTS devices are employed. This paper presented the application of Static Var Compensator to the Nigerian 330kV Power Network to study its effect on the system's active transmission loss. SIMULINK/MATLAB was used to model the Nigerian 330kV Power Network and the SVC. The simulation result showed that by applying the Static Var Compensator, the systems total active transmission loss was reduced by 31.79%. From the above percentage reduction and the pattern of the associated chart and graph, it was observed that SVC could be used for active transmission loss minimization in power systems.

Keywords: FACTS, Active transmission loss, Static Var Compensator, SIMULINK, Electrical power

INTRODUCTION

Modern civilization has resulted in continuously increasing demand for electrical power in every sector of life [1]. The demand has imposed many challenges on the power industry due to the radical changes in the energy market as power demand is more than the availability [2]. The challenges include: overloading of transmission and distribution lines, lost of voltage stability and high power losses [3]. These challenges have consequently affected the performance of operating loads and resulted in blackouts in several countries including Nigeria. All the attempts made by the government in conjunction with the Generation Companies (GENCO), Transmission Companies of Nigeria (TCN), and Distribution Companies (DISCO), for instance, the establishment of new power generation plants which requires huge amount of funds have not in any way helped the situation.

Several studies [4] [5], [6], [7], [8], [9] etc have shown that most of the power quality issues are direct consequence of variations in the system's reactive power. Reactive power is essential for voltage stability maintenance in power systems and has direct effect on its transmission capability [10]. Thus, adequate reactive power compensation is necessary in power systems [11]. The primitive ways of reactive power compensation include [12]: system structure reconfiguration, regulation of generator excitation, synchronous generator, tap changing of transformer voltage, switching in/out the shunt reactor or shunt capacitor and series compensation capacitor.

The primitive methods could not achieve the desired objectives as the mechanical components are prone to wear or tear and exhibit slow response to system changes [12]. Flexible AC transmission Systems (FACTS) technology with near-instantaneous response with no mechanical wear or tear was employed to improve power system performance without generation rescheduling and topology changes [8], [13], [14] .

FACTS devices are capable of improving voltage stability and minimize transmission losses of complex power systems [15], [16], [17]. "FACTS devices also play an important role for demand side management and thereby controlling transmission line congestion" [18]. FACTS devices include: Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Static VAR Compensator (SVC), Thyristor-Controlled Phase Shifter (TCPS), Interline Power Flow Controller (IPFC) and Static Synchronous Compensator (STATCOM) [12] [19], [20].

In [21], the use of STATCOM which is one the FACTS devices for power loss minimization was presented. However, this paper studies the effect of SVC in minimizing power system active transmission loss through adequate reactive power compensation using the Nigerian 330kV power network for the study and SIMULINK/MATLAB as the simulation environment

THE STATIC VAR COMPENSATOR (SVC)

SVC is used to provide fast operating reactive power control in power systems[5]. They use a combination of capacitors and reactors for fast control of power system variables [22]. They are employed in power systems for several purposes, the primary of which is rapid control of voltage at weak points in a network [23]. Installations may be at the midpoint of transmission interconnections or at the line ends. In its simple form, SVC is connected as Thyristor-Controlled-Reactor Fixed Capacitor (TCR-FC) configuration. The TCR-FC conventional diagram and equivalent circuit are as shown in Figure 1 (a) and (b) respectively. TCR-FC has the following components: coupling transformer, thyristor valves, reactors, and capacitors (for harmonic filtering) [12].

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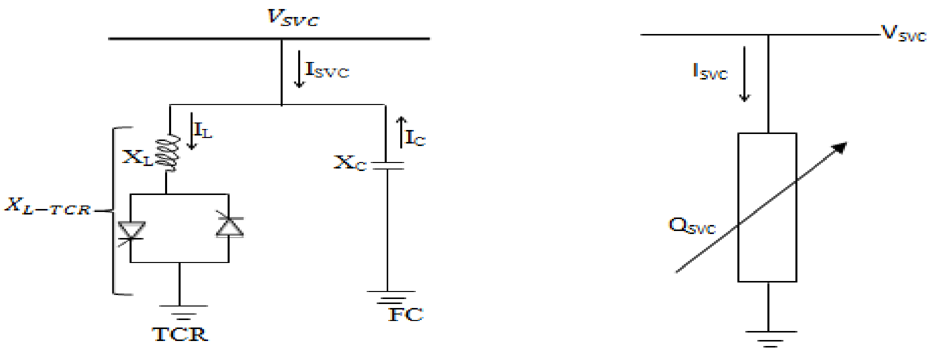

Figure 1: (a) Conventional TCR-FC SVC (b) SVC Equivalent Circuit [12]

THE POWER SYSTEM USED FOR THE STUDY

The power system used for the study is as shown in Figure 2. It is the Nigerian 330kV power system network obtained from PHCN Control Centre, Oshogbo along with its relevant data which is as shown in table 1

A. MODELING OF THE NIGERIAN 330KV POWER SYSTEM USING SIMULINK/MATLAB

Using MATLAB/SIMULINK, the Nigerian 330kV power network was implemented as shown in Figure 3. The generation stations were represented as voltage sources while the transmission lines were represented by their equivalent resistances and reactance. Measuring tools i.e. ammeter, wattmeter and voltmeter as well as the modeled SVC were incorporated in the model [12].

B. ACTIVE TRANSMISSION LOSS ESTIMATION

To determine the transmission losses in the lines, let us consider a cross section of the transmission line between any giving bus A and B shown in Figure 4.

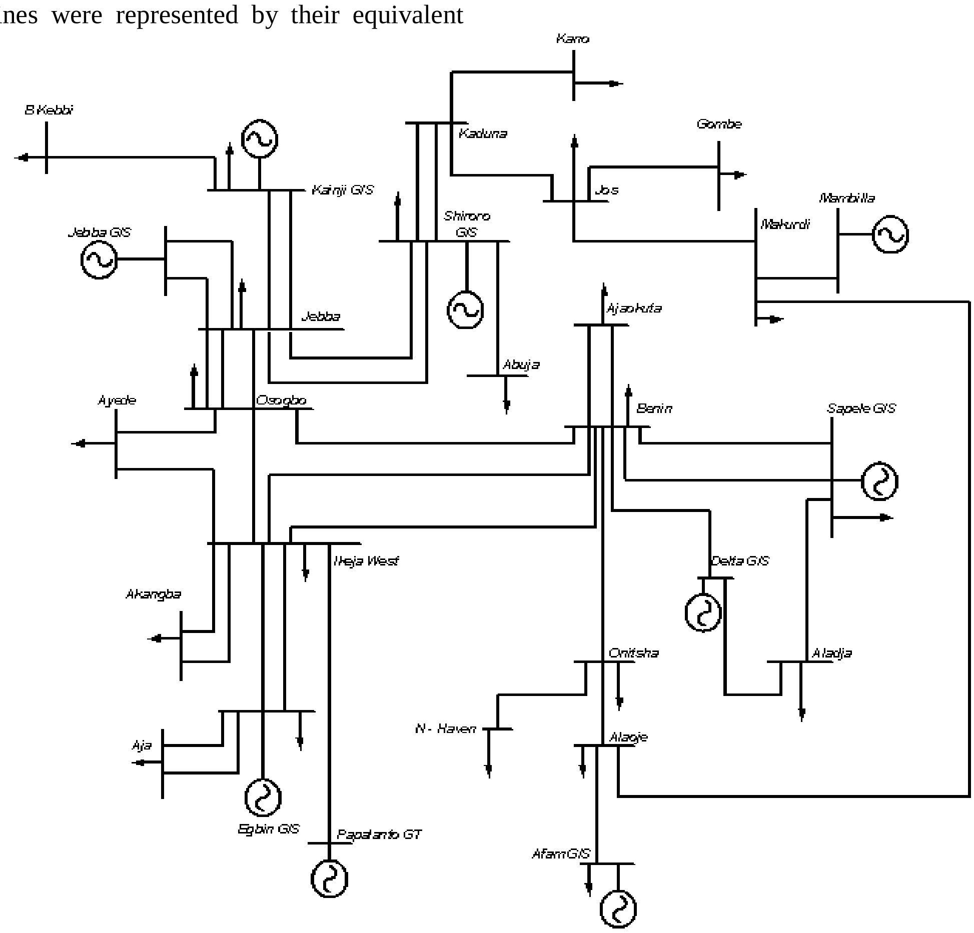

Figure 2: The Nigerian 330kV Power Network [12]

Table 1: Relevant Data of the Nigerian 330kV Power Network [12]

Bus Identification		Bus Loads		Transmission Lines Data			
Name	No	MW	MVAR	Bus		Resistance R(pu)	Reactance X(pu)
				FROM	TO		
Egbin	1	68.90	51.70				
Delta	2	0.00	0.00	1	3	0.0006	0.0044
Aja	3	274.40	205.80	4	5	0.0007	0.0050
Akangba	4	244.70	258.50	1	5	0.0023	0.0176
Ikeja-West	5	633.20	474.90	5	8	0.0110	0.0828
Ajaokuta	6	13.80	10.30	5	9	0.0054	0.0405
Aladja	7	96.50	72.40	5	10	0.0099	0.0745
Benin	8	383.30	287.50	6	8	0.0077	0.0576
Ayede	9	275.80	206.8	2	8	0.0043	0.0317
Osogbo	10	201.20	150.90	2	7	0.0012	0.0089
Afam	11	52.50	39.40	7	24	0.0025	0.0186
Alaoji	12	427.00	320.20	8	14	0.0054	0.0405
New-Heaven	13	177.90	133.40	8	10	0.0098	0.0742
Onitsha	14	184.60	138.40	8	24	0.0020	0.0148
B/Kebbi	15	114.50	85.90	9	10	0.0045	0.0340
Gombe	16	130.60	97.90	15	21	0.0122	0.0916
Jebba	17	11.00	8.20	10	17	0.0061	0.0461
Jebba G	18	0.00	0.00	11	12	0.0010	0.0074
Jos	19	70.30	52.70	12	14	0.0060	0.0455
Kaduna	20	193.00	144.70	13	14	0.0036	0.0272
Kanji	21	7.00	5.20	16	19	0.0118	0.0887
Kano	22	220.60	142.90	17	18	0.0002	0.0020
Shiroro	23	70.30	36.10	17	23	0.0096	0.0271
Sapele	24	20.60	15.40	17	21	0.0032	0.0239
Abuja	25	110.00	89.00	19	20	0.0081	0.0609
Makurdi	26	290.10	145.00	20	22	0.0090	0.0680
Mambila	27	0.00	0.00	20	23	0.0038	0.0284
Papalanto	28	0.00	0.00	23	25	0.0038	0.0284
				12	26	0.0071	0.0532
				19	26	0.0059	0.0443
				26	27	0.0079	0.0591
				5	28	0.0016	0.0118

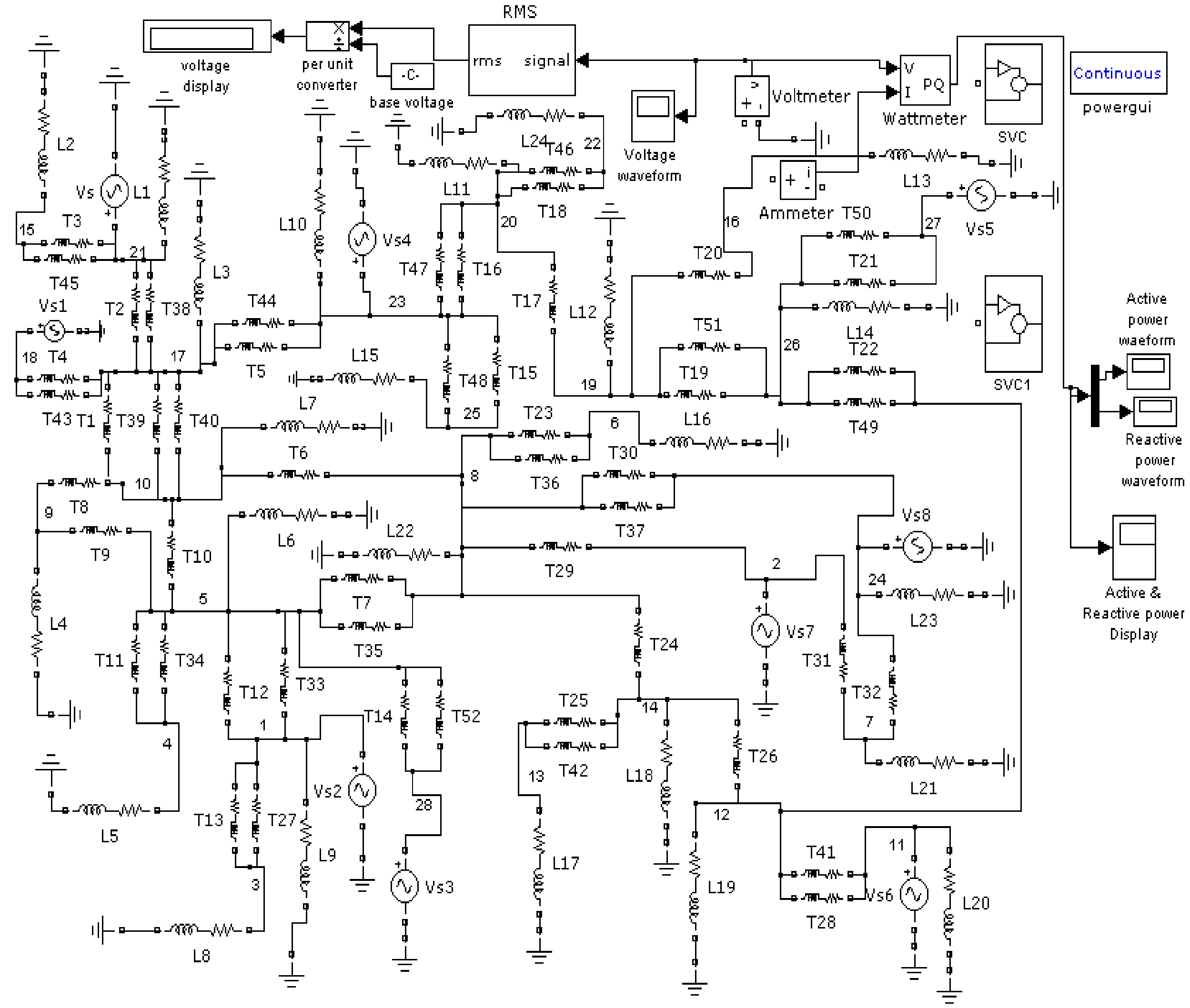

Figure 3: The Nigerian 330kV power Network modeled using SIMULINK

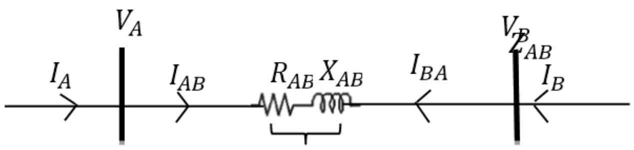

Figure 4: A section of a transmission line

All symbols used in Figure 4 are defined as follows [12]:

I_A = Current injected into bus A

V_A = Bus A voltage

I_B = Current injected into bus B

V_B = Bus B voltage

I_{AB} = Current flowing from bus A to bus B

I_{BA} = Current flowing from bus B to bus A

R_{AB} = the transmission line resistance

X_{AB} = the transmission line reactance

From Figure 4;

$$I_A = I_{AB} \tag{1}$$

$$I_A = -I_{BA} \tag{2}$$

$$I_{AB} = (V_A - V_B)y_{AB} \tag{3}$$

$$I_{BA} = (V_B - V_A)y_{AB} \tag{4}$$

$$Z_{AB} = R_{AB} + jX_{AB} \tag{5}$$

$$y_{AB} = \frac{1}{Z_{AB}} \tag{6}$$

Using (5) in (6) will give;

$$y_{AB} = \frac{1}{R_{AB}+jX_{AB}} \tag{7}$$

From (7),

$$y_{AB} = \frac{R_{AB}-jX_{AB}}{R_{AB}^2+X_{AB}^2} \tag{8}$$

Equation (8) can be expressed as:

$$y_{AB} = \frac{R_{AB}}{R_{AB}^2+X_{AB}^2} - \frac{jX_{AB}}{R_{AB}^2+X_{AB}^2} \tag{9}$$

If we let;

$$G_{AB} = \frac{R_{ABik}}{R_{AB}^2 + X_{AB}^2} \quad (10)$$

$$B_{AB} = -\frac{X_{AB}}{R_{AB}^2 + X_{AB}^2} \quad (11)$$

Substituting equations (10) and (11) in (9) yields;

$$y_{AB} = G_{AB} + jB_{AB} \quad (12)$$

Complex power, S_{AB}, flowing from bus A to bus B is giving by [12];

$$S_{AB} = V_A I_A^* \quad (13)$$

Using (1) in (13) will give;

$$S_{AB} = V_A I_{AB}^* \quad (14)$$

The complex power is a vector sum of the real (P) and reactive (Q). As a result, it can also be expressed as;

$$S_A = P_A + Q_A \quad (15)$$

Comparing equations (13) and (14), we have;

$$S_{AB} = P_{AB} + Q_{AB} \quad (16)$$

Comparing equations (14) and (16) and taking the conjugate of both sides will give;

$$P_{AB} - Q_{AB} = V_A^* I_{AB} \quad (17)$$

Using (3) in (17), we have;

$$P_{AB} - Q_{AB} = V_A^*(V_A - V_B) y_{AB} \quad (18)$$

Combining (12) and (17) yields;

$$P_{AB} - Q_{AB} = V_A^*(V_A - V_B)(G_{AB} + jB_{AB}) \quad (19)$$

Expressing (19) in polar form yields;

$$P_{AB} - Q_{AB} = V_A < -\sigma_A(V_A < \sigma_A - V_B < \sigma_B)(G_{AB} + jB_{AB}) \quad (20)$$

Expanding and simplifying (20) yields;

$$P_{AB} - Q_{AB} = (V_A^2 - V_A V_B < (\sigma_B - \sigma_A))(G_{AB} + jB_{AB}) \quad (21)$$

$$P_{AB} - Q_{AB} = V_A^2(G_{AB} + jB_{AB}) - V_A V_B < (\sigma_K - \sigma_A)(G_{AB} + jB_{AB}) \quad (22)$$

Expanding (22) will give;

$$P_{AB} - Q_{AB} = V_A^2 G_{AB} + jV_A^2 B_{AB} - V_A V_B G_{AB} < (\sigma_B - \sigma_A) - jB_{AB} V_A V_B < (\sigma_B - \sigma_A) \quad (23)$$

Expressing (23) in trigonometric form and equating the real and imaginary parts gives

$$P_{AB} = V_A^2 G_{AB} - V_A V_B G_{AB} \cos\theta_m + B_{AB} V_A V_B \sin\theta_m \quad (24)$$

$$Q_{ik} = -V_A^2 B_{AB} + V_A V_B G_{AB} \sin\theta_m - B_{AB} V_A V_B \cos\theta_m \quad (25)$$

Where $\theta_m = \sigma_B - \sigma_A$

Similarly,

$$P_{BA} = V_B^2 G_{AB} - V_A V_B G_{AB} \cos\theta_m - B_{AB} V_A V_B \sin\theta_m \quad (26)$$

$$Q_{BA} = -V_B^2 B_{AB} - V_A V_B G_{AB} \sin\theta_m - B_{AB} V_A V_B \cos\theta_m \quad (27)$$

Note: for power flowing from bus B to bus A; $\theta_m = -(\sigma_B - \sigma_A)$

The active transmission loss (P_{LAB}) between bus A and bus B is given by;

$$P_{LAB} = P_{AB} + P_{BA} \quad (28)$$

Adding (24) and (26) gives;

$$P_{AB} + P_{BA} = V_A^2 G_{AB} - V_A V_B G_{AB} \cos\theta_m + B_{AB} V_A V_B \sin\theta_m + V_B^2 G_{AB} - V_A V_B G_{AB} \cos\theta_m - B_{AB} V_A V_B \sin\theta_m \quad (29)$$

Using (28) in (29) yields;

$$P_{L_{AB}} = G_{AB}(V_A^2 + V_B^2 - 2V_A V_B \cos\theta_m) \quad (30)$$

Assuming that the Static Var Compensator is applied to bus B, then equation (30) can be re-written as:

$$P_{L_{AB}} = G_{AB}(V_A^2 + V_{SC}^2 - 2V_A V_{SC} \cos\theta_m) \quad (31)$$

By regulating the voltage at bus k thereby keeping the power factor close to unity, the Static Var Compensator is able to minimize the system's active transmission loss.

Equation (30) and (31) gives the active transmission loss of the system without and with Static Var Compensator respective. However, in this research work, the real power flowing from any giving bus A to B and vice-versa was measured using the wattmeter and recorded. Thereafter equation (28) was used to estimate the active transmission loss.

C. THE STATIC VAR COMPENSATOR MODEL

TCR-FC SVC was used in this study. Its functional and equivalent circuit diagrams are as shown in Figures 1 (a) and (b) respectively.

It is evident from Figure 1 that SVC has two branches with one being purely inductive and the other purely capacitive and so does not consume real power [12]. Thus SVC reduces the system's voltage by using its reactive branch to consume reactive power and its capacitive branch increases the system's voltage by injecting reactive power into the network. The reactive power consuming reactor has its current (I_{TCR}) to be positive while the reactive power injecting capacitor has its current (I_{FC}) to be negative. Thus the SVC current (I_{SVC}) at maximum var could be expressed as follows [12]:

$$I_{SVC} = I_{TCR} - I_{FC} \quad (32)$$

Where:

$$I_{FC} = \frac{V_{SVC}}{X_{FC}} \quad (33)$$

$$I_{TCR} = \frac{V_{SVC}}{X_{TCR}} \quad (34)$$

X_{FC} =Capacitive reactance of the SVC = $\frac{1}{2\pi f C}$ (35)

X_{TCR} =Inductive reactance of the SVC = $2\pi f L$ (36)

From figure 1 (b), $P_{SVC} = 0$ since SVC does not consume active power.

But we have,

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$$Q_{SVC} = I_{SVC} \times V_{SVC} \quad (37)$$

By comparing equations (32) and (37) we have:

$$Q_{SVC} = (I_{TCR} - I_{FC}) \times V_{SVC} \quad (38)$$

Combining equations (33), (34) and (38), we have:

$$Q_{SVC} = \left(\frac{V_{SVC}}{X_{TCR}} - \frac{V_{SVC}}{X_{FC}}\right) \times V_{SVC} \quad (39)$$

$$Q_{SVC} = \left(\frac{1}{X_{TCR}} - \frac{1}{X_{FC}}\right) \times V_{SVC}^2 \quad (40)$$

$$Q_{SVC} = \frac{X_{FC} - X_{TCR}}{X_{TCR} X_{FC}} V_{SVC}^2 \quad (41)$$

The design of the SVC controller was such that the TCR is switched off when the bus voltage falls below the reference voltage and vice-versa. Thus, at maximum var absorption the TCR and FC operate such that;

$$Q_{SVC}^{max} = \frac{X_{FC} - X_{TCR}}{X_{FC} X_{TCR}} V_{SVC}^2 \quad (42)$$

And at minimum var absorption $I_{TCR} = 0$, so that;

$$Q_{SVC}^{min} = -\frac{1}{X_{FC}} V_{SVC}^2 \quad (43)$$

At $Q_{SVC} < 0$, SVC injects reactive power into the network while at $Q_{SVC} > 0$, SVC consumes reactive from the network.

For this study, 100 MVA base was used for power. 1.0 and 0.5 p.u. respectively were assumed for SVC parameters, X_{FC} and X_{TCR}. With the given values of SVC parameters and base power, Q_{SVC}^{min} and Q_{SVC}^{max} for

this case study are -100 and 100 Mvar respectively. The limits of the bus voltage, V_{SVC} (V_{min} and V_{max}) are 0.95 and 1.05 p.u. (i.e. 1 ± 0.05) respectively. With these limits, the bus of application of SVC with a base voltage of 330kV will have a voltage limit as shown below: $313.5 \leq V_{SVC} \leq 346.5$ (kV)

Buses 5 and 13 had the least voltage when the system was run without SVC. As result the two SVCs used in this study were applied at the two buses.

D. SIMULINK MODEL OF THE STATIC VAR COMPENSATOR*:*

SIMULINK blocks were used to model the TCR-FC SVC as shown in Figure 5. In the model, L stands for Reactor, Th for thyristor, FC for Fixed Capacitor and Tr1 for Step down Transformer.

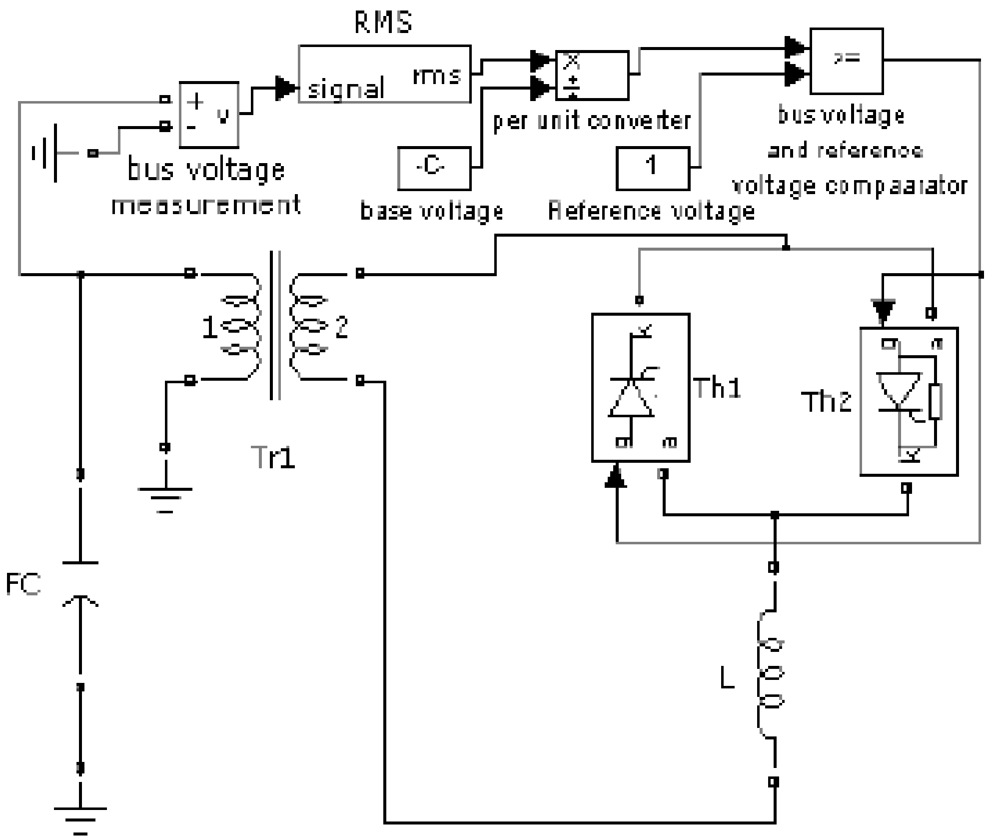

Figure 5: SVC and its Controller modeled using SIMULINK

RESULTS AND DISCUSSION

The simulation results for real power flow and the losses when the network was run without and with SVC are as shown in Table 2

Table 2: Real power flow and losses when the system was run without and with SVC

Bus		Active Power Flow(MW) without SVC		Active Power Loss(MW) without SVC $\lvert P_{AB} - P_{BA} \rvert$	Active Power Flow(MW) with SVC		Active Power Loss(MW) with SVC $\lvert P_{AB} - P_{BA} \rvert$
A	B	P_{AB}	P_{BA}		P_{ik}	P_{ki}	
1	3	137.3	-136.9	0.4	137	-136.6	0.4
1	5	429.3	-429.7	4.6	486	-490.6	4.6
2	8	63.73	-63.5	0.23	73.25	-73.46	0.21
2	7	32.67	-32.85	0.18	32.54	-32.59	0.05
4	5	-170.4	170.7	0.3	-172.2	172.3	0.1
5	8	-41.91	41.73	0.18	-46.7	46.6	0.1
5	9	70.12	-69.84	0.28	66.21	-66.6	0.39
5	10	-13.26	13.28	0.02	-17.84	17.84	0
6	8	-6.86	6.85	0.01	-6.85	6.87	0.02
7	24	-15.66	15.62	0.04	-15.63	15.61	0.02
8	14	86.67	-86.59	0.08	134.5	-134.4	0.1
8	10	9.91	-10.02	0.11	8.18	-8.18	0
8	24	-273.6	272.1	1.5	-314.9	314.1	0.8
9	10	-65.32	65.2	0.12	-69.84	69.9	0.06
15	21	-57.26	56.87	0.39	-56.7	56.86	0.16
10	17	-168.1	169.3	1.2	-180	179.7	0.3
11	12	387.8	-389.9	2.1	431.4	-430.5	0.9
12	14	89.72	-89.15	0.57	135.7	-135.6	0.1
13	14	-84.8	84.12	0.68	-178.6	178.9	0.3
16	19	-63.48	62.95	0.53	-62.91	63.39	0.48
17	18	-157.2	156.3	0.9	-166.6	167.1	0.5
17	23	-4.41	4.41	0.01	-4.65	4.66	0.01
17	21	-13.45	13.35	0.1	-14.07	14.09	0.02
19	20	-30.53	30.55	0.02	-31.34	31.38	0.04
20	22	108	-108.3	0.3	107.9	-107.7	0.2
20	23	-234.2	233.6	0.6	-235.7	234.9	0.8
23	25	54.66	-55.16	0.05	54.92	-55.05	0.13
12	26	85.47	-85.14	0.33	82.32	-82.03	0.29
19	26	-67.18	66.99	0.19	-66.49	66.34	0.15
26	27	-125.2	125.1	0.4	-127.9	128.3	0.1
5	28	-73.86	73.56	0.63	-92.84	93.47	0.3
TOTAL				17.05			11.63

A. CORRELATION BETWEEN THE ACTIVE POWER LOSSES WITH/WITHOUT SVC

In order to acknowledge the appreciable effect of SVC on the power system's active transmission loss, it is expedient to compare the system's active power losses without/with SVC. Figures 6 and 7 which obtained using the results in table 2 were used for the comparison.

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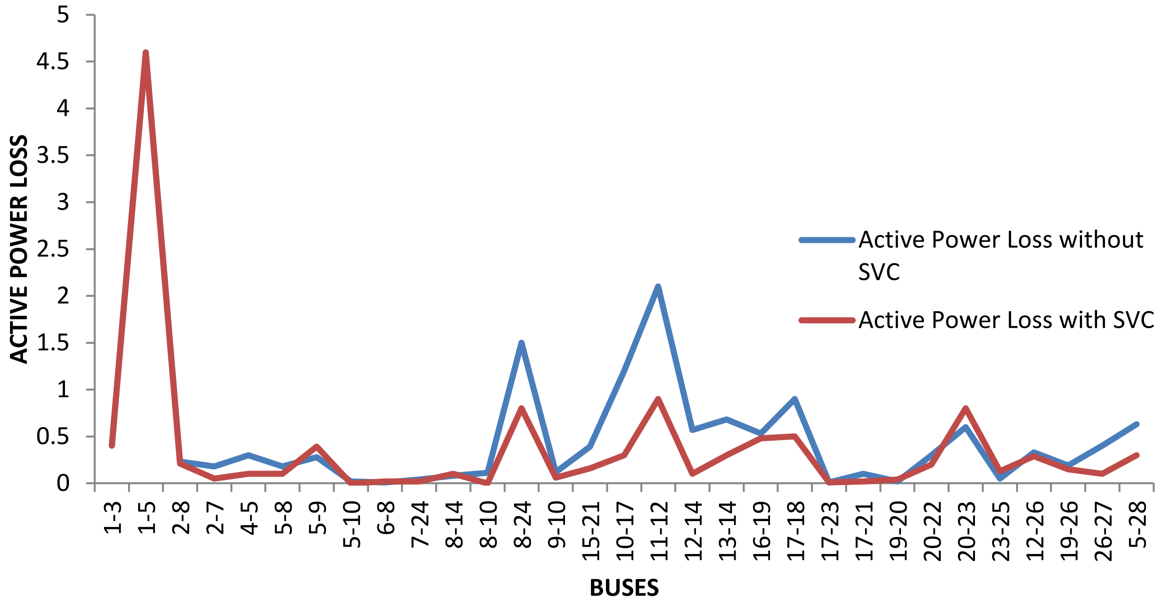

Figure 6: Graph Representing the Active Power Losses without/with SVC

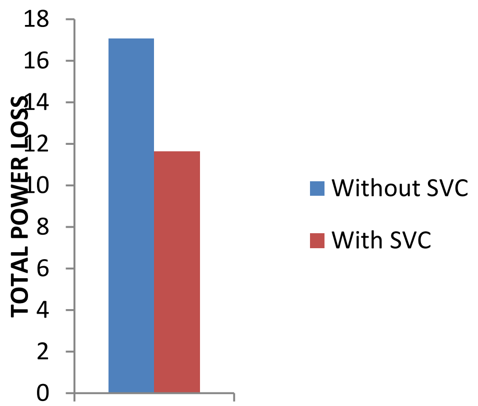

Figure 7: Chart Representation of the Total active power loss without/with SVC

Table 2 shows that the Nigerian 330kV network losses 17.05MW and 11.63MW of its total active power when it was run without and with SVC respectively. Comparison between the two indicates that, there was 31.79% reduction in the total active power loss when SVC was applied to the system. Figures 6 and 7 also indicate that the system's active power loss was appreciably reduced when SVC was applied. Thus it can be deduced that SVC application can greatly reduce transmission loss in power systems.

CONCLUSION

In this paper, lack of adequate reactive power compensation was identified to have been responsible for most of the power quality issues such as voltage instability, transmission loss and power factor fluctuations. The use of Static Var Compensator for solving power quality issues especially the transmission loss was proposed. SIMULINK/MATLAB was used to model the Nigerian 28-bus power system using the data obtain from PHCN power control centre, Oshogbo, as well as two Static Var compensators. In SIMULINK/MATLAB environment, the Nigerian 330kV network was simulated without and then with the SVCs. From the result of the simulation, its, the active power loss for both cases were estimated and compared using a graph and bar chart. The comparison showed that with SVC, the real power loss in the power system was greatly reduced. It could therefore worth concluding that the Static Var compensator could be used to achieve active transmission loss reduction in power systems.

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