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The Use of Static Var Compensator (SVC) In Transmission Congestion Management of a Restructured Nigerian Power System

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ABSTRACT

The restructuring of power system is expected to always result in an increased overloading of the transmission networks due to increased activities of power system investors. These activities usually lead to the congestion on the transmission line. Transmission congestion has very negative consequences on the power systems which include system collapse and severe system damage. Nigerian power system has an average operational generation capacity of 3,879MW with a total installed generation capacity of 12,522MW. It therefore becomes necessary to access the readiness of the transmission lines for increased power system activities. In this paper, a comprehensive load flow study was carried out on 41-bus Nigeria power systems and voltage violations were observed in 16 buses. Two basic methods used in congestion management are cost-free and non-cost free methods. The Static VAR Compensator (SVC) is a cost-free method that was applied in this work. SVCs were placed in the 16 buses while an Optimal Power Flow (OPF) solution was run. The result obtained showed that the bus voltage profile of the power system network was improved and returned to the acceptable limits of 0.95pu – 1.05pu while the MVA flow of the lines was also balanced. All simulation work was carried out in Power System Analysis Toolbox (PSAT) in MATLAB 2014 Software.

Key words: Restructuring, congestion, transmission, load flow, voltage violations, generation

1. INTRODUCTION

Electrical power system is a composite network which is made up of generation, transmission and distribution with interlinked accessories (facilities). The transmission line facilities aid the final consumers of power to access the generated energy at the terminus. The key factors that are responsible for the Nigeria Power Sector restructuring as referenced in [1] are combinations of poor power generation, lack of capital for power expansion and investment, ineffective regulation, high technical losses, insufficient transmission and distribution facilities, inefficient use of electricity by consumers, inappropriate industry and market structure, unclear delineation of roles and responsibilities of the Nigeria electricity industry. Prior to restructuring, the Power Holding Company of Nigeria (PHCN) enjoyed the monopoly of controlling the activities of generation, transmission and distribution of electricity. After undergoing restructuring, the operating principles of the transmission company becomes clearly defined so that different investors are able to forecast the profit margins and the reliability of the network. These increased activities of the investors exert pressure on the transmission lines hence the expected congestion of the line. In 2011, Nigeria had an installed capacity of 8, 910MW and over 12, 132MW in 2015 [2] which when put into operation is expected to increase pressure on the existing transmission line. At the moment, power industry is undergoing restructuring and deregulation in various countries across the globe with the replacement of previous monolithic regulated public utilities with the competitive power markets [3]. This is to meet the increasing demands for electricity around the world at affordable prices [4]. Transmission congestion in power system occurs when power flow over a transmission line exceeds the available capacity due to increase in scheduled market transactions (generation and load). Congestion also occurs when power flow in the transmission line are higher than the flow allocated by the operating reliability limits [5].The following factors can lead to the Congestion of the transmission line:

i. Outages of the Generator (s)
ii. Outages of the Transmission line
iii. Changes in energy demand
iv. Uncoordinated transactions
v. Violations in existing and new contracts

The transmission lines have to be managed so as to withstand these increased pressure of constant change in energy demand. Several techniques of managing congestion in transmission network are reported in [6-10]. In this paper, Static VAR Compensator was used in transmission congestion management of a restructured Nigerian Power system while the newly improved active Nigerian 41-bus system was considered and simulated in this work.

2. THE 41 BUS NIGERIAN TRANSMISSION GRID NETWORK

Transmission lines form a central nexus between the generation and the distribution units and hence an important part of power systems. The Transmission Company of Nigeria (TCN) manages the electricity transmission network in the country. The Nigerian transmission network is made up of high voltage substations with a total (theoretical) transmission wheeling capacity of 7,500MW and over 20,000km of transmission lines [11]. Currently, transmission wheeling capacity (5,300MW) is higher than average operational generation capacity of 3,879MW but it is far below the total installed generation capacity of 12,522MW [11].

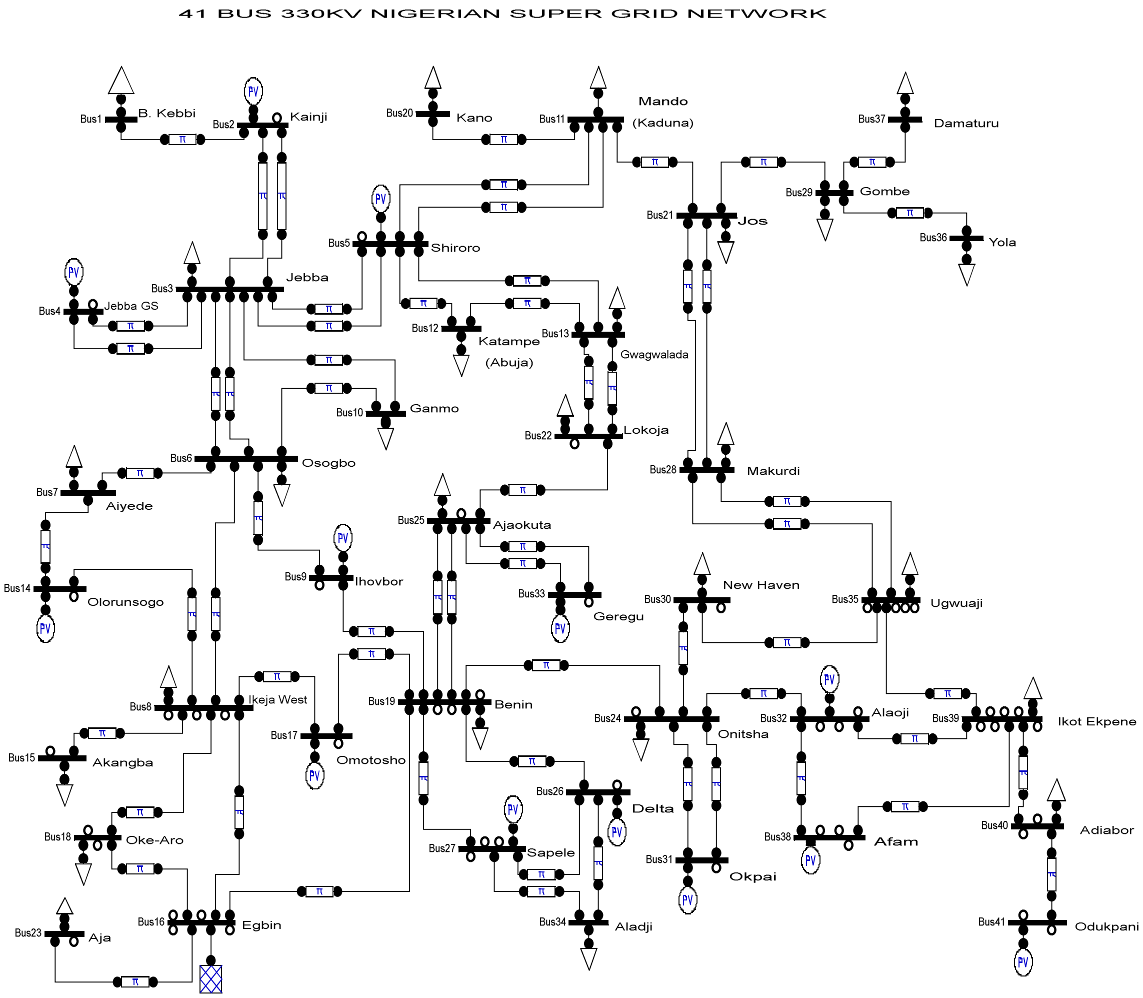

Figure 1: 41 Bus 330KV a restructured Grid Network [6]

The growth of transmission network should be in line with the expected increase in generation. In a restructured power system network, different generating companies are expected to compete for opportunities to sell power to different buyers (Distribution companies). These transactions must pass through the transmission network hence the need to check if the network is robust enough for this increase or the need to expand the network. The growths in generation station expansion in Nigeria are shown in Table. 1. The newly improved active Nigerian 41-bus system considered includes the generating stations contributing power to the grid. The one-line diagram of the 41-bus Network is shown in Figure 1.

Table -1 Nigerian Generation Power Growth

S/N	Period	Installed Capacity (MW)
1.	1960-1969	760
2.	1970-1979	0
3.	1980-1989	2788
4.	1990-1999	600
5.	2000-2009	2435
6.	2010-2019	6788
7.	2020 - 2022	826
8.	Yet to be commissioned	1030

In Table 1, there has been a surge in the installed capacity of generating stations since the power reform in 2005 and eventual restructuring in 2013. Therefore, great concern should be made on the transmission network to ensure its readiness in evacuating all these power when fully operational. One of the means of accessing the capacity of the transmission network is the Transmission Congestion Management. In a vertically integrated utility structure, the activities of both transmission and generation are under the control of a single entity hence power is dispatched through the least cost operating mechanism. This implies that power generation is dispatched so that power flow limits on the transmission lines are not exceeded [12]. The scenario changes in a deregulated power system environment since the distribution sector wishes to buy electricity from the cheapest available generation irrespective of the location of buyer and seller. As a result of this, evacuating this generated power from the cheaper generators would get the transmission routes overloaded if all such transactions are simultaneously approved. This may aggravates if the Nigerian transmission lines are not capable of carrying out these transactions without a veritable means of the real time congestion management. For a successful deployment of the Transmission Congestion technique, a load flow analysis of the network was done to ascertain the buses and lines with voltage and MVA violations respectively.

3. LOAD FLOW ANALYSIS AND PROBLEM FORMULATION

Load flow analysis gives the information about the voltage magnitude and angle at the buses, the line MVA flows and the line losses. The essence of the load flow in this case is to determine the voltage violations with respect to the base case voltage. This will enable us know the areas to install the congestion management mechanism. Load flow solution techniques include the following: Gauss-Seidel method, Newton Raphson method and Fast Decoupled method. Referring to a 2-bus system of a transmission line as shown in Figure 2, the voltages at the buses are presented in equations (1) and (2):

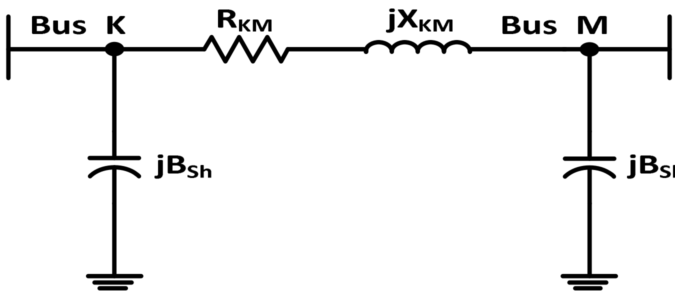

Figure 2: Two Bus Transmission Line

$$V_k = V_k < \theta_k \tag{1}$$
$$V_m = V_m < \theta_m \tag{2}$$

Also, the real and reactive power flow along transmission line (neglecting the shunt admittances of the line) from *k* to *m* are shown in equations (3) and (4) respectively.

$$P_k = V_k V_m (G_{km} cos\, \theta_{km} + B_{km} sin\theta_{km}) - V_k^2 G_{km} \tag{3}$$
$$Q_{km} = V_k V_m (G_{km} sin\theta_{km} - B_{km} cos\, \theta_{km}) - V_k^2 (B_{km} + B_{sh,km}) \tag{4}$$

For an n-bus power systems, the real and reactive power flow along the lines are as presented in equations (5) and (6) respectively.

$$P_k = \sum_{m=0}^{n} /V_k// V_m/(G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m) \qquad (5)$$

$$Q_k = \sum_{m=0}^{n} /V_k// V_m/(G_{km}\sin(\theta_k - \theta_m) - B_{km}\cos(\theta_k - \theta_m) \qquad (6)$$

Where, V_k *and* V_m are the complex voltages at buses *k* and *m* respectively.
G_{km} *and* B_{km} are the real and imaginary parts of the Y_{km},
$B_{sh,km}$ is the shunt susceptance associated with the π-model of the transmission line,
θ_{km} is the voltage angle at the buses.
There are different methods of load flow analysis but the important ones are categorized as: Gauss-Seidel method, Newton-Raphson method and Fast Decoupled method [13]. A Newton-Raphson technique is found to be more efficient and practical methods to the solution of the power flow problems because they are less prone to divergence with ill-conditioned problems [14] and therefore was used in this paper. Load flow analysis for this 41-bus power system was done using PSAT. The flow chart for this technique and the subsequent congestion management strategy is shown in Figure 3.

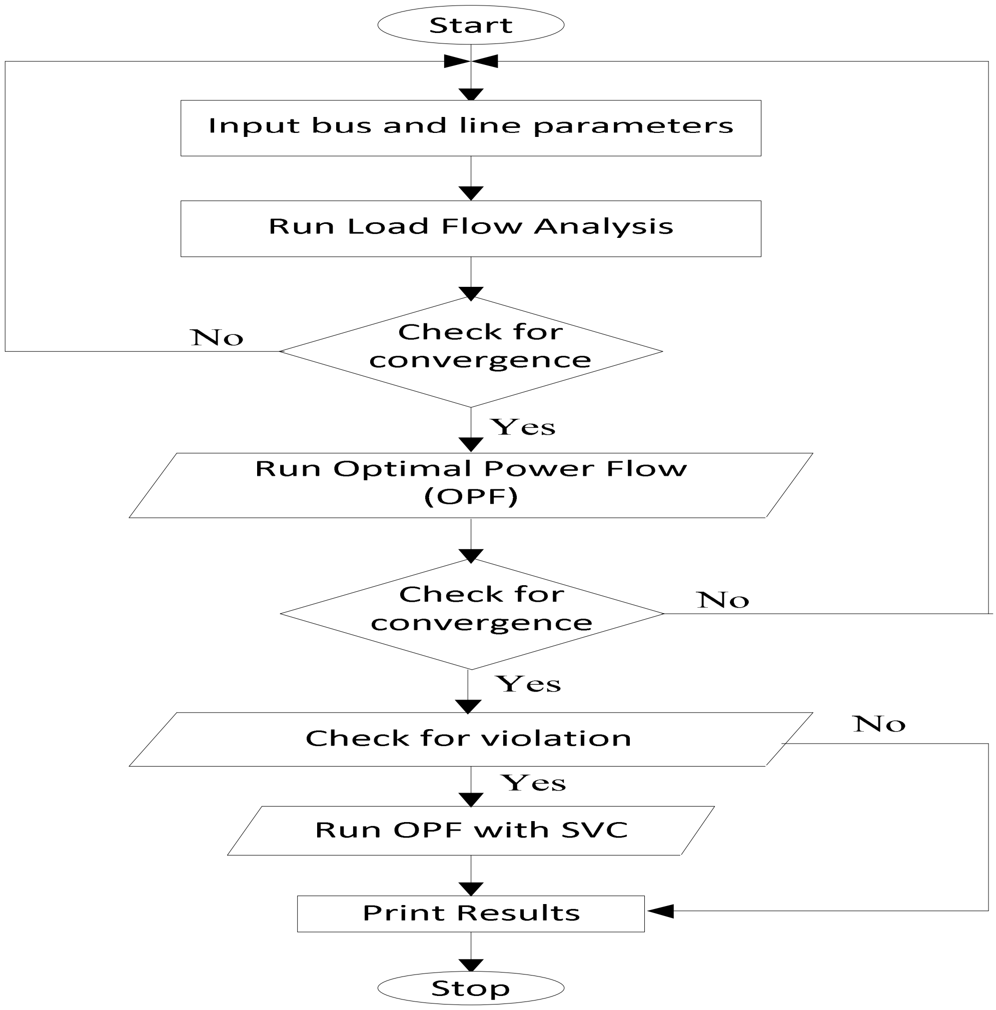

Figure 3: Formulation Flow Chart

4. STATIC VAR COMPENSATORS (SVC)

As the activities of the power wheeling process increases, there is every tendency that congestion would occur on the power system network. Therefore, there are two ways of relieving this congestion; the cost-free method and non-cost-free method. The use of FACTs Devices is a cost-free method used to remove transmission line Congestion. The FACTS device is a power electronics device employed to control the Power Flow and improve the stability of power system. According to [15], FACTS devices are static power-electronic devices installed in AC transmission networks to increase power transfer capability, stability, and controllability of the networks through series and/or shunt compensation.

The working principle of the FACTS is to use power electronics-controlled devices to regulate power flows in a transmission line so as to enable the line to be loaded to its full capacity [16]. The FACTS device among other things ensure increased power transfer capacity, series and shunt impedance control, stability improvement of the grid system, and bus voltage control. The different types of FACTS devices include: Series, Shunt and combination of Series and Shunt devices. Shunt Var Compensator (SVC) is a shunt compensating type of FACTS devices. It is designed to maintain bus voltage magnitude. SVC is capable of generating and consuming reactive powers. This makes it an ideal device in network voltage control [17]. SVC is made up of thyristor controlled reactors (TCRs) and thyristor switched capacitors (TSCs). Either of the TCRs, TSCs or the combination can be used to maintain constant voltage levels, enhance power flow, improve stability and provide load angle improvements [18]. The control strategy with Static Var Compensator is to ensure that the bus voltages at the transmission lines are kept within a small firing angle. The limits of the angle are in the range of ($180^0 > \propto > 90^0$). Once the firing angle runs outside the limits, there is a violations. The Optimal Power Flow (OPF) of the power system is run with optimal placement of SVC to ensure that the presence of violations in the transmission lines is removed. SVCs were placed on some buses to see its effectiveness in improving the voltages at the respective buses after the load flow analysis of the network was carried out. The structure and equivalent circuit of SVCs shown in Figure 4 is a combination of TCR and TSC. From the equivalent circuit of Figure 4 (b), the current at bus k is given by equation (7).

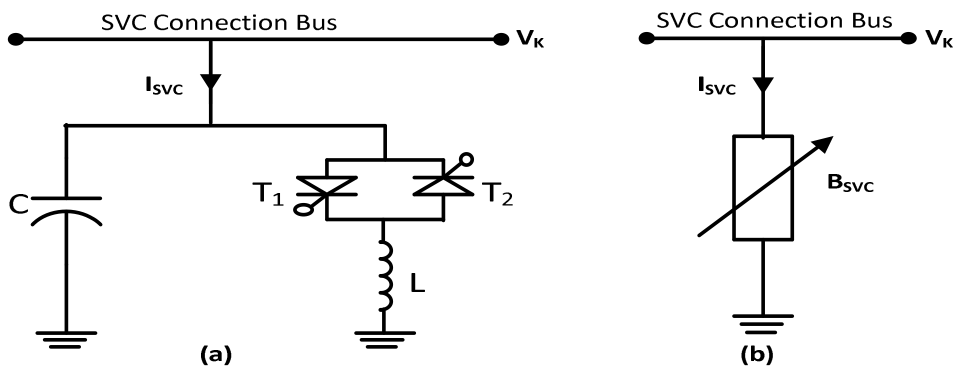

Figure 4 : TCR type SVC structure and its Equivalent Circuit

$$I_{SVC} = jB_{SVC}.V_k \quad (7)$$

Also, the reactive power injected to the bus, k from the SVC as referenced in [19] is given by equation (8).

$$Q_{SVC} = V_k^2.B_{SVC} \quad (8)$$

The reactive power injected to the bus depends on the firing angle of the TCR. At 0^0, full current passes through the inductor hence injecting more reactive power to the bus. But when the firing angle is at 180^0, the current then passes through the capacitor hence limiting the quantity of reactive power passing through to the bus.

5. SIMULATION RESULTS AND DISCUSSIONS

Power System Analysis Toolbox (PSAT) is the software used for simulations in this work. PSAT is a MATLAB toolbox for electric power system analysis and simulations [20]. PSAT is purely MATLAB based and the Simulink environment provides the required tools for the network design [21]. Power system voltage violations can be under voltage or over voltage. SVC devices regulate and control these voltage violations to the required acceptable set points. From the results of the load flow analysis, voltage violations occurred at 16 buses as shown in Table 2. SVCs were placed at those buses to improve the voltage magnitude at the point of violation as shown in Figure 5 while the results obtained after connection are presented in Figure 6. The acceptable operating range of voltages is between 0.95pu – 1.05pu for the 330kV grid voltage (313.5kV – 346.5kV). Also, the MVA loadings of the lines are presented in Table 3.

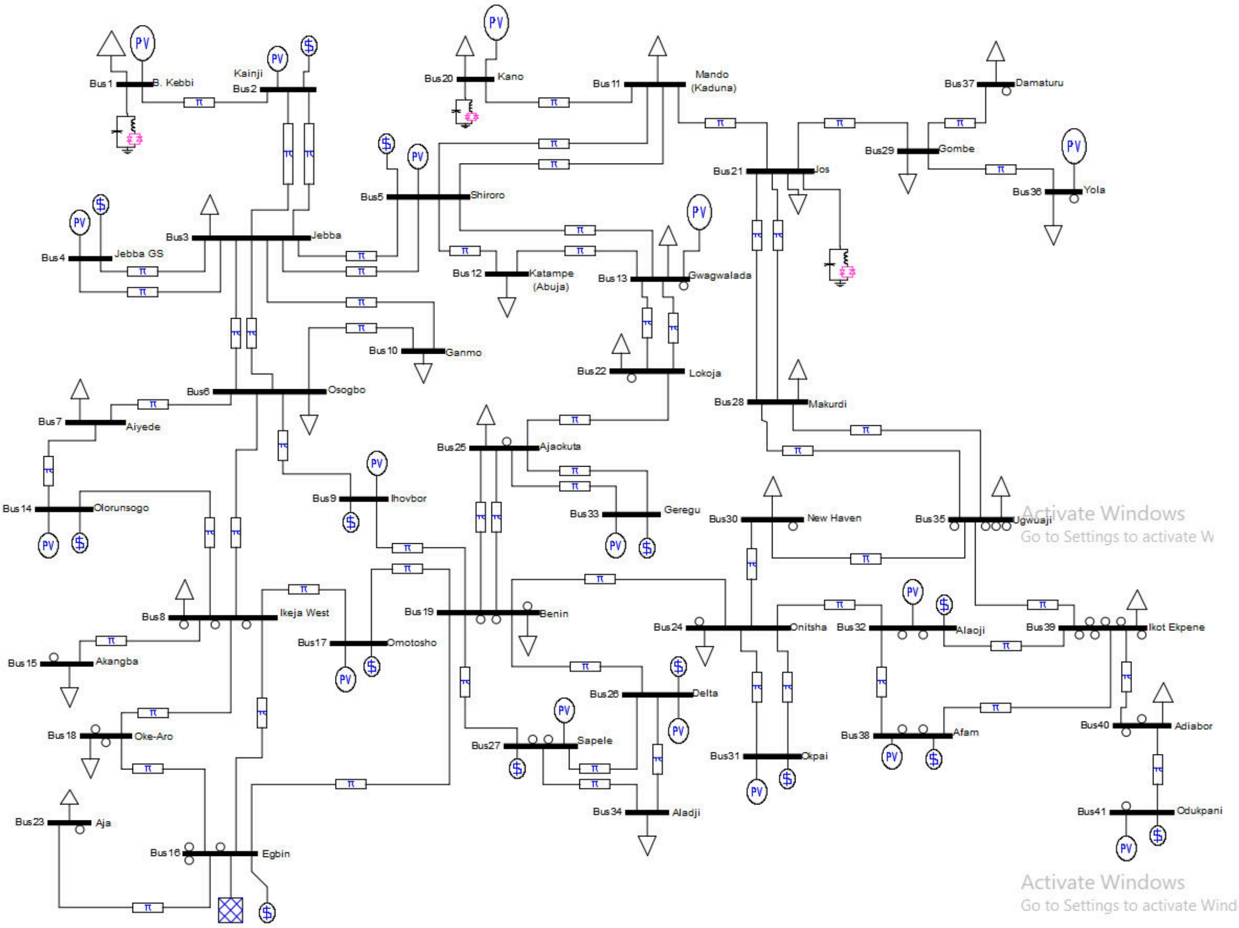

Figure 5: Connection of SVCs to the voltage violating points of the 41-bus Power system

Table 2: Bus voltage Profile after SVC placement

Bus No.	Bus Voltages (kV)	Bus voltages after connection of SVCs (kV)
1.	293.253555	332.150312
7.	311.684035	317.098603
8.	311.764469	318.049407
11.	312.449814	334.305090
12.	305.322129	323.177229
13.	307.862055	329.048118
15.	308.423972	314.778754
20.	303.040173	333.057674
21.	273.792810	342.731554
22.	310.769754	327.168601
28.	270.786292	332.020369
29	234.0070032	333.958029
30.	284.016960	320.249962
35.	282.299036	321.181084
36.	226.518147	330.311920
37.	228.005352	329.841823

Table -3 MVA loadings of the lines after SVC placement

Line Name	Bus Connections	Base Case	SVC
		MVA FLOW	MVA FLOW
Line 16	Egbin – Benin	1077.486573	299.3829
Line 23	Benin – Onitsha	723.4804368	654.6983
Line 17	IKeja West – Oke-Aro	632.8807493	591.0460
Line 18	Oke-Aro – Egbin	674.9173576	746.1466
Line 19	Ikeja West – Omotosho	557.6037835	92.98644
Line 27	Benin – Sapele	724.4299672	333.0255
Line 34	Onitsha – Alaoji	652.7435806	158.2730
Line 55	IkotEkpene – Ugwaji	787.0385312	88.88702
Line 62	Adiabor – Odukpani	570.8668234	90.90880
Line 14	Egbin – Ikeja West	527.6949407	563.6300

In table 2, the voltage profiles at the buses were all within the acceptable range when SVCs were placed. Also, in table 3 Line 16 (Egbin) was generating above its capacity which resulted in high congestion around the adjoining lines. The SVC when connected was able to reduce the loadings on the transmission lines. For example, line 16 was relieved of heavy loadings and distributed to lines 14 and 18 as shown in Figure 6.

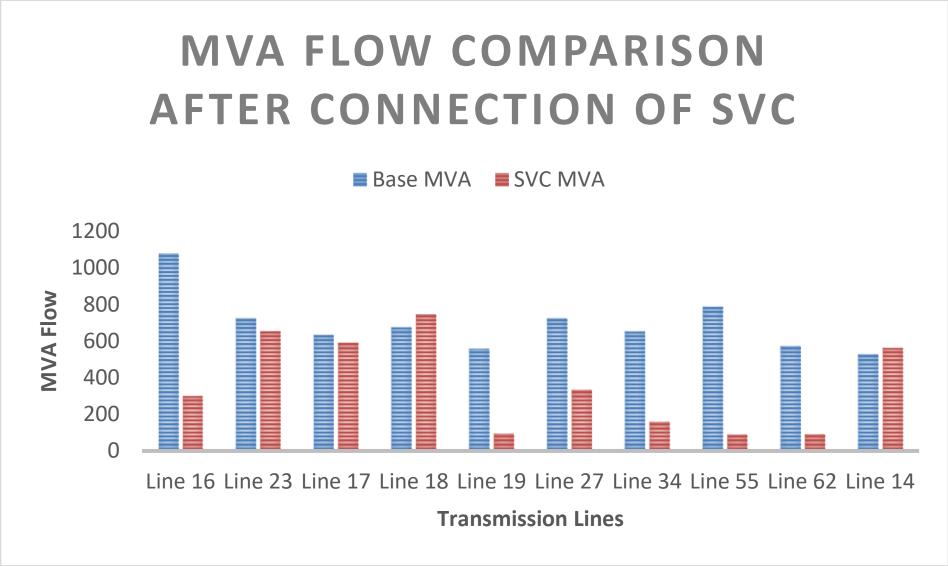

Figure 6: MVA Flow Comparison after Connection of SVC

6. CONCLUSIONS

This work considered the use of the cost free congestion management technique for the transmission congestion management of the Nigerian improved 41-bus power system after deregulation. The cost free technique used is the installation of SVC to the buses with voltage violations after the power flow analysis. The SVC was connected to each bus with cases of violations in the Nigerian 41-bus system. The bus voltages returned to the acceptable limits of (0.95pu – 1.05pu) after the placement of the SVC. Also MVA loadings was found to be very high around bus-line 16 (Egbin) because the bus was the only generator bus that was found delivering to its near capacity hence the congestion. The SVC ensured that wheeling of power was balanced around line 14 (Egbin – Ikeja West), line 16 (Egbin – Benin) and line 18 (Oke-Aro – Egbin). This showed that SVC placement resulted in an improved bus voltage profile in case of wheeling transaction and contingency condition. It also balanced the MVA flows in the lines.

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