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IMPROVING THE TRANSIENT STABILITY OF NIGERIAN 330KV TRANSMISSION NETWORK USING STATIC VAR COMPENSATION PART I: THE BASE STUDY

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ABSTRACT

In this paper, the base study for improving the transient stability of Nigerian 330kV transmission network using Static Var Compensation (SVC) is conducted with the focus of developing indices that can appropriately size and locate SVC within the network. The study is performed using commercially available software Dig SILENT Power Factory. The overloaded lines which could excite instability in the network are identified. Fixed capacitor thyristor controlled reactor is used to model the SVC and is appropriately sized and located within the network. Transient stability of the network is analysed by determining the critical clearing time of the acute generators when a balanced three phase fault is applied to the middle of the critical lines within the network using step-by step technique. Some of the key results reveal that the lines: Jebba- Osogbo, Shiroro-Kaduna, Benin-Sapele and Benin-Onitsha are the critical lines within the network. The Critical Clearing Times (CCTs) of the acute generators when 3-phase fault is applied at Jebba- Osogbo and Shiroro-Kaduna transmission lines are 380ms and 480ms, respectively. However, generators located at Afam and Sapele that are close to Benin-Sapele and Benin-Onitsha transmission line, respectively are always losing synchronism to 3-phasefault of any duration. Appropriately sized SVCs with values 124Mvar, 73Mvar, 62Mvar and 110Mvar located at Osogbo, Kaduna and Benin compensated the network and increase the CCTs to 470ms, 500ms, 220ms and 120ms, respectively.

Keywords*: Dig SILENT Power Factory, Transient Stability, Static Var Compensation, Nigerian 330kV transmission line.*

1. INTRODUCTION

In recent years, transmission networks are overloaded and are pushed closer to their stability limits. This is as a result of increasing demand for electricity due to growing population. This could have negative effect on the power system security. The security of a power system is regarded as the ability of the network to withstand disturbances without breaking down [1]. One of the indices to assess the state of security of a power system is the transient stability [2] and it involves the ability of power system to remain in equilibrium or return to acceptable equilibrium when subjected to large disturbances [3]. Various methods of determining the transient instability in power system includes numerical integration, direct method, probabilistic method [2] and the artificial intelligent methods such as artificial neural networks [4]. Generally, transient stability is evaluated by the system Critical Clearing Time (CCT) in response to various large disturbance such as faults, loss of large load, loss of generation and major lines loss [5]. CCT gives the maximum duration of time a power system can remain stable under a given large disturbance condition[6]. The robustness of a power system is largely determined by its response to the disturbances. A higher value of CCT denotes a robust and better secured system [7].

One of the factors that determine the level of integrity of a power system (i.e. transmission capability limit and flexibility of power system) is the level of security of the network based on transient stability assessment[8].Therefore, power system grid integrity can be enhanced by devising a means of improving transient stability[9]. The use of Flexible AC

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Transmission Systems (FACTS) devices have been identified as cost effective means of improving the transient stability without the need for constructing new transmission lines [10]. Several FACTS devices have been proposed for improving the power system operation and they are [11]: the Static Var Compensator (SVC), Controllable Series Compensator (CSC), Phase Shifter (PS), Series Capacitors (SC), Thyristor Controlled Series Capacitors (TCSC), Unified Power Flow Controller (UPFC), Convertible Series Compensator (CSC), Inter-phase Power Flow Controller (IPFC), Static Synchronous Series Controller (SSSC), STATCOM etc. Of these various FACTS devices, SVC is found to be effective for transient stability improvement when appropriately sized[12]and is now forming an integral part of modern electrical power systems [2]. It is one of the key devices that exhibit instantaneous response to system changes and are fabricated from solid semi-conductor components [13]. SVCs are basically shunt connected and are usually installed at the midpoint of the transmission line or at the line ends through a coupling transformer[14]. It has the ability of improving transient stability by dynamically controlling it's reactive power output [15].

Nigeria power system is faced with series of technical challenges due to long, radial, weak and aging transmission network[16]. Different studies have been done on Nigerian 330kV transmission network by various indigenous researchers with each researcher focusing on different aspect of performance assessment with a view to improve the network: Technical losses on the 330kV Nigerian transmission losses has been studied by Anumaka [17]. The mathematical analysis in relation to Nigerian power system technical losses was derived. Onojo *et al* [18] has performed reliability and efficiency assessment of the proposed (post reform) 10,000MW capacity 330kV transmission network and also determined the extent to which it will provide solution to the numerous problems that presently plague the existing power system network. It was concluded that construction of new grid will reduce losses and improve the reliability and efficiency of the network. Similarly, Izuegbunam et al [19] utilized Power World Simulator to compare the proposed post expansion network with that of the existing 330kV transmission network with a view of estimating the real and reactive power flows, power losses as well as the bus voltage angle. The simulation result reveals that 85.3MW losses occurred in the existing grid, while the expanded and fortified grid showed a reduce power losses of 32MW and 24.7MW, respectively. Onohaebi and Igbinovia [20] are concerned with the assessment of voltage dip of the post expansion network in comparison with the existing Nigeria 330kV network. Their result showed that the incorporation of some additional lines to form more loops would improve the Nigerian 330kV network to acceptable voltage limits of $\pm 5\%$ which could have positive influence on the reliability and security of the network. Similarly, Ogunjuyigbe and Awosope [21] are of the opinion that adequately sized and optimally located reactor could improve the network voltage profile to the acceptable limit of $\pm 5\%$. Recently, an improvement of voltage stability of Nigerian 330kV network was studied by Mathew *et al* [22] using SVC. The result showed that, the system's voltage stability was improved by about 33.78% indicating a significant improvement in the system's voltage stability when SVCs were applied.

Most of the aforementioned studies are concerned with either the expansion/fortification of the existing network, the voltage profile improvement or power loss reduction in order to improve the system security by expanding the existing network. This present paper aims at investigating the improvement of the transient stability of the Nigerian 330kV transmission network by appropriately sizing and locating SVC within the network. In this way the security of the system is improved thereby challenging the need for immediate construction of new transmission lines. This would allow time for proper planning for a later upgrade. The Nigerian network was modelled using commercially available software Dig SILENT Power Factory. The overloaded lines which could trigger transient instability in the network were identified. The critical clearing time before and after the installation of SVC were compared .Results in this paper could be useful as initial technical information that could help in the future expansion and operation planning of the Nigerian 330kV transmission network. Though the size and location of SVCs in this paper was determined using "*wheel barrow*" approach, the result obtained could serve as a base study to develop various indices that could aid optimal sizing and placement of SVCs within the Nigerian power network.

2. NIGERIA 330KV TRANSMISSION NETWORK

The Nigeria 330kV power system used in this study consists of 7 main power stations which cut across the country with long radial interconnected lines. The network consists of 5,523.8km of lines with total installed transformation capacity of 5,687.32 MVA (equivalent to 4,832 MW). The transmission network is depicted in

Figure 1. The transmission line and the generator data are given in Tables 6 and 7 in the appendix.

Identification Buses and the Generators			
BusNo	Name	BusNo	Name
1	B/Kebbi	20	Ikeja-West
2	Kainji	21	Akangba
3	Jebba	22	Egbin
4	Kainji TS	23	Egbin TS
5	Jebba TS	24	Aja
6	Jebba TS	25	Sapele TS
7	Osogbo	26	Aladja
8	Shiroro	27	Delta TS
9	Shiroro TS	28	Afam TS
10	Kaduna	28	Afam
11	Ajaokuta	30	Delta
12	Kano	31	Sapele
13	Jos	G1	Kainji Generator
14	Gombe	G2	Jebba Generator
15	Benin	G3	Egbin Generator
16	Onitsha	G4	Shiroro Generator
17	New Haven	G5	Delta Generator
18	Ayede	G6	Sapele Generator
19	Alaoji	G7	Afam Generator

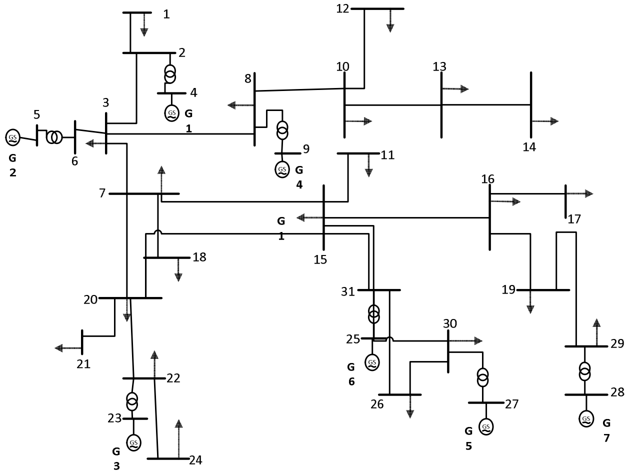

Figure 1: Nigeria 31 bus, 7 Generator, 330kV Transmission System as at 2006

3. THE MODEL APPROACH

3.1 Synchronous Generator Model

Detailed model in which the transient and sub-transient phenomena are considered [3] was used for modelling of all synchronous generator within the network in rotor reference frame[23]. The mechanical variables are linked with the electrical variables as follows:

$$\frac{J\omega_n^2}{P_z^2 P_r}\frac{dn}{dt} = T_m + T_e \qquad (1)$$

Where J is the inertia, ω_n is the angular speed, p_z is the pole pair number, T_m and T_e are the mechanical and electromagnetic torques of the machine. The normalized per unit inertia (H) of the generator and the turbine is expressed as inertia time constant given in equation (2)

$$H = \frac{1}{2}\frac{J\omega_0^2}{P_z^2 P_r} \qquad (2)$$

where ω_0 is the synchronous speed.

The electromagnetic torque expressed in terms of the stator flux and stator current is given as:

$$T_e \psi_d i_q - \psi_q i_d \qquad (3)$$

where ψ_d and ψ_q are stator fluxes.

3.2 Power System Model and Load Flow Study

Electric power network are modelled by sets of non-linear equations that describe the state of the power system[24]. The model requires that the real power and bus voltages of the generators within the network be specified [25]. This is because it is convenient to specify real power for all generators and to use the generator bus voltage instead of reactive power [26]. Load flow study is performed on the network model to solve the non-linear algebraic equations. This allows the determination of the bus voltages magnitude, its corresponding angle as well as power flows for specified generation and bus conditions [27]. There are several algorithms for performing load flow analysis[28]. However, Newton-Raphson technique is adopted in this study because; it is faster and converges in most cases compared to the other methods. Although, it requires large computer memory, but can be overcome through a compact storage scheme [29].

For an 'n'buses, the admittance matrix of the network can be written as:

$$\begin{bmatrix} I_1 \\ I_2 \\ \cdot \\ \cdot \\ \cdot \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{1n} \\ Y_{21} & Y_{22} & Y_{2n} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ .\,Y_{n1} & Y_{n2} & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ \cdot \\ .\,V_n \end{bmatrix} \qquad (4)$$

where $I_{(.)}$ is the current flow within the network, $V_{(.)}$ is the bus voltages and $Y_{(i,j)}$ is the bus admittance between buses i and j within the network. The active and reactive powers injected into each bus can be derived as (5) and (6)

$$P_i = \sum_{k-1}^{n} |V_i||V_k|\,|Y_{ik}|\cos(\theta_{ik} - \delta_k) \qquad (5)$$

$$Q_i = -\sum_{k-1}^{n} |V_i||V_k|\,|Y_{ik}|\sin(\theta_{ik} - \delta_k) \qquad (6)$$

Where V_i is voltage magnitude at bus i, θ_i is bus I voltage angle, δ_{ik} is admittance angle while Y_{ik} is the admittance linking bus i to k

The voltage magnitude and its angle are calculated iteratively using Newton-Raphson's procedure following the determination of P_i and Q_i in (5) and (6).It is indicative that both the real and reactive powers are functions of $(|V|, \delta)$;

$$\begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (7)$$

where J_1, J_2, J_3 and J_4 are the elements of the Jacobian matrix in equation (7), the variables at the end of each iteration are updated as below:

$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)}$ and $\left|V_i^{(k+1)}\right| = \left|V_i^k\right| + \Delta\left|V_i^k\right|$ for $i=1,2,\dots n$. Solution converges when ΔP and ΔQ are obtained lower than stipulated tolerance.

The apparent power at each bus is given as:

$$S_i = P_i + jQ_i = V_i I_i \qquad (8)$$

and the bus current is evaluated using:

$$I_i = \frac{P_i - jQ_i}{V_i} \qquad (9)$$

The summary of the steady state result after performing the load flow of the Nigerian 330kV transmission network is depicted in Tables1and 2. Table 1 revealed that the total grid loss in the network is 15.67MW with a total spinning reserve of 94.83MW. Results from Table 2 showed that the bus voltages are within ±5% limit indicating no voltage violation under the steady state condition. However, the tie lines Benin -Onitsha, Jebba-Osogbo, Shiroro- Kaduna and Benin -Sapele are overloaded as depicted in Figure 2. As such the lines are identified as critical lines in this study because it could cause transient instability in the network in the event of any large disturbance on any of the lines. In view of the primary goal of this paper, it will investigate the network transient stability should a fault occur on any of these critical lines.

Table 1: Summary result of the Steady State analysis

	Active Power (MW)	Reactive Power(MVar)	Apparent Power(MVA)
Generation	4737.17	3147.20	5687.32
Grid Losses	15.67	-86.70	
Line Charging		-362.45	
Installed Capacity	4832.00		
Spinning Reserve	94.83		

Table 2: Steady State busbar voltages and angles

BUS NUMBER	BUS NAME	VOLTAGE	
		MAGNITUDE (p.u)	PHASE ANGLE (deg.)
1	B/Kebbi	0.96	-5.71
2	Kainji	1.02	-0.89
3	Jebba	1.01	-1.03
4	Kainji GS	1.03	0.41
5	Jebba GS	1.03	0.28
6	Jebba TS	1.01	-1.03
7	Osogbo	1.01	-1.30
8	Shiroro	1.01	-1.41
9	Shiroro GS	1.03	-0.09
10	Kaduna	1.00	-1.88
11	Ajaokuta	1.01	-1.84
12	Kano	0.98	-3.37
13	Jos	0.98	-3.32
14	Gombe	0.96	-4.99
15	Benin	1.01	-1.62
16	Onitsha	1.00	-3.07
17	New Haven	0.99	-3.34
18	Aiyede	0.99	-1.83
19	Alaoji	1.00	-2.82
20	Ikeja-West	0.99	-1.88
21	Akangba	0.99	-1.87
22	Egbin	0.99	-1.62
23	Egbin GS	1.00	0.00
24	Aja	0.99	-1.62
25	Sapele GS	1.03	-0.59
26	Aladja	1.02	-1.32
27	Delta GS	1.04	0.02
28	Afam GS	1.02	-1.46
29	Afam	1.00	-2.80
30	Delta	1.02	-1.27
31	Sapele	1.02	-1.48

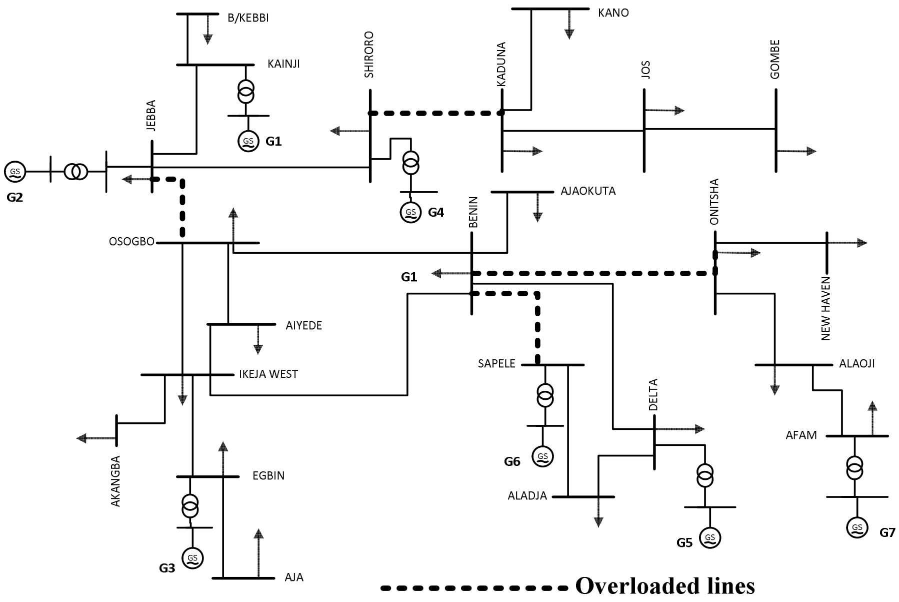

Figure 2: Nigerian 330kV highlighting overloaded transmission lines

3.3 Transient Stability

Transient stability of Nigerian 330kV network was carried out using step by step approach based on evaluation of Critical Clearing Time (CCT). An indicator of the system stability is given by the rotor angle of the machines and the critical clearing time (CCT) of the system before losing equilibrium[30]. The rotor angle (δ_i) of i^{th} generator using the step by step procedure for multi-machine system like that of Nigerian grid can be determined by the following non-linear differential equations (10-12), [31]. The step by step procedure for determining the critical clearing time of the network is depicted in Figure 3.

$$\frac{d\delta_i}{dt} = \omega_r$$

$$M_i \frac{d\omega_r}{dt} = P_{mi} - P_{ei};\, i = 1,2 \ldots \mathrm{n} \qquad (11)$$

Where

$$P_{ei} = E_i^2 \mathrm{Y_{ii}} \cos\theta_{ii} + \sum_{j=1\ j\neq i}^{n} E_i E_j E_{ij}\ \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \qquad (12)$$

δ_i is the rotor angle of the generator, M_i is the inertia coefficient, P_{ei} is the electrical power, P_{mi} is the mechanical power, E_i is the internal voltage of the generator, Y is the reduced admittance matrix, Y_{ij} is the *ij*-th element of the reduced admittance matrix. The parameters M_i, P_{mi} and E_i are assumed to be constant values. The electrical power of the x-*th* stable generator and the y-*th* critical generator are derived from (12) as (13) and (14), respectively[31]:

$$P_{ex} = E_x^2 \mathrm{Y}_{xx} \cos\theta_{xx} + \sum_{j\in S} E_x E_j E_{xj}\ \cos\left(\delta_a - \delta_s - \theta_{xj}\right) + \sum_{j\in A, j\neq x} E_x E_j E_{xj}\ \cos\theta_{xj} \qquad (13)$$

$$P_{ey} = E_y^2 \mathrm{Y}_{yy} \cos\theta_{yy} + \sum_{j\in A} E_y E_j E_{yj}\ \cos\left(\delta_s - \delta_a - \theta_{yj}\right) + \sum_{j\in S, j\neq y} E_y E_j E_{yj}\ \cos\theta_{yj} \qquad (14)$$

'a' represents a stable generator, 's' represents a critical generator, and 'A' represents group of all other generators.

3.4 Modelling of SVC for Transient Stability Improvement

The SVC used in this paper is a fixed capacitor thyristor controlled reactor (FC-TCR) type as depicted in Figure 4.

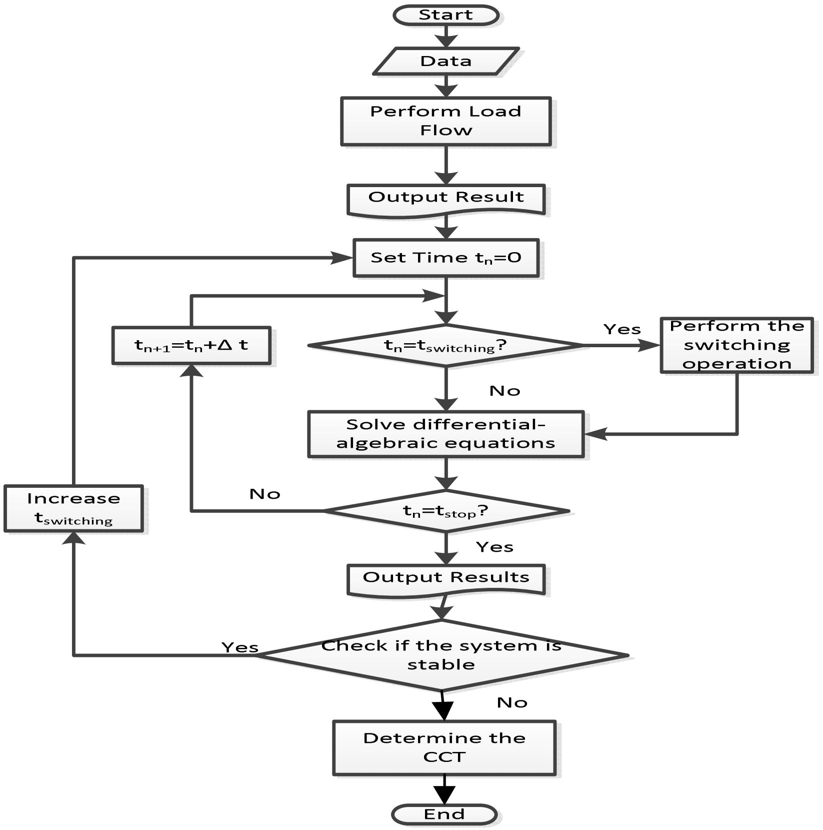

Figure 3: Step-by-step procedure for determining the CCT of the transmission network

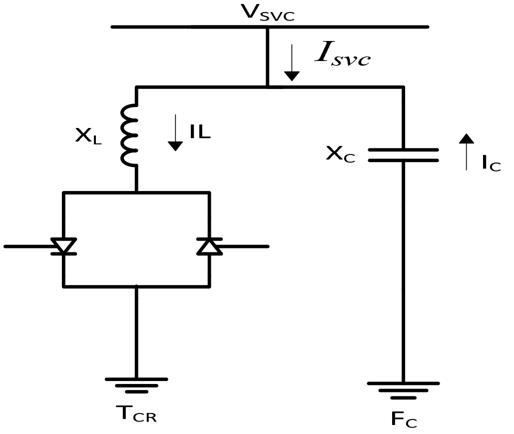

Figure 4: Functional diagram of a FC-TCR

One of the SVC branch is purely capacitive while the other is inductive. As a result, the SVC consumes no active power. However, it has the capability of either consuming reactive power through the inductive branch (T_{CR}) so as to reduce the system's voltage or injecting reactive power into the system through the capacitive branch (F_C) in order to increase the voltage. The reactor current I_L is positive, while the capacitor current I_C is negative. Thus, SVC current (I_{SVC}) value at maximum var is expressed as follows:

$$I_{SVC} = I_L - I_C \qquad (15)$$

Where $I_c = \frac{V_{SVC}}{X_C}; I_L = \frac{V_{SVC}}{X_L}$, and V_{svc} is the bus voltage magnitude.

$$\text{but } \frac{1}{X_L} = B_L(a) = \frac{2(\pi - a) + \sin(2a)}{\pi X_L}; \frac{\pi}{2} \le \alpha \le \pi \qquad [32]$$

where α is the gate firing angle and hence

$$I_L = V_{SVC} \times B_L(\alpha) \qquad (16)$$

Since no active power is taken by the SVC, the reactive power consumed can be expressed as:

$$Q_{SVC} = I_{SVC} \times V_{SVC} \qquad (17)$$

where V_{SVC} is the bus voltage,
Substituting (15) into (17), yields the following:

$$Q_{SVC} = (I_L - I_C) \times V_{SVC} \qquad (18)$$

Substituting (16) into (18) yields:

$$Q_{SVC} = \left(B_L(\alpha) - \frac{V_{SVC}}{X_c}\right) \times V^2{}_{SVC} \qquad (19)$$

$$Q_{SVC} = \left(B_L(\alpha) - \frac{1}{X_c}\right) \times V^2{}_{SVC} \qquad (20)$$

The equivalent susceptance of the SVC ($B_{SVC}(\alpha)$) can be written as:

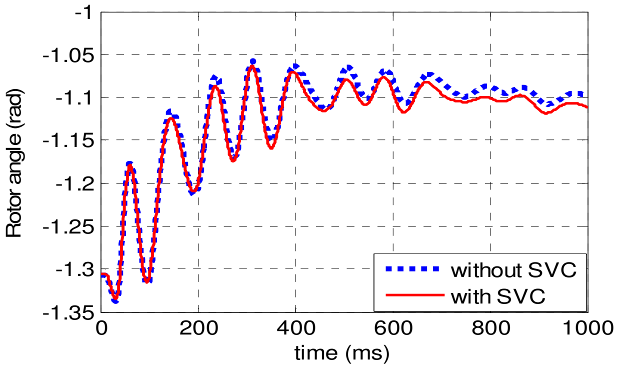

Figure 5: Response of generator rotor angle at Jebba with and without SVC following a 3-phase fault

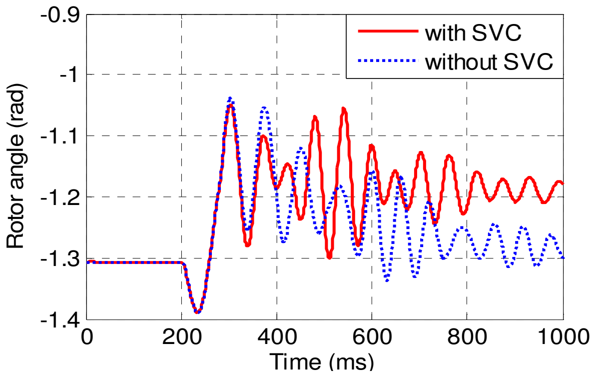

Figure 6: Rotor angle plot of the Generator at Shiroro with and without SVC following a 200ms 3-phase fault

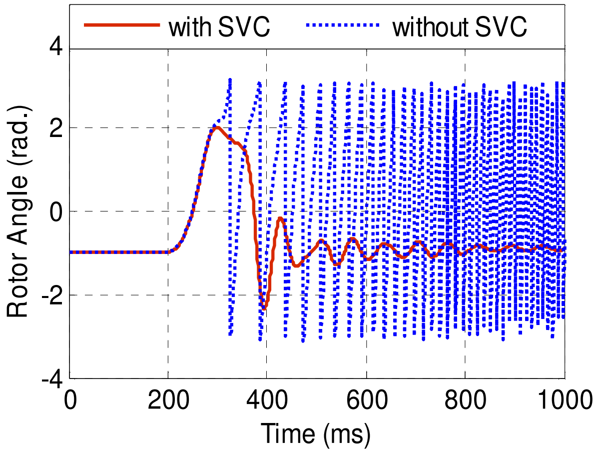

Figure 7: Rotor angle plot of the generator located at Sapele with and without SVC following a 3phase fault

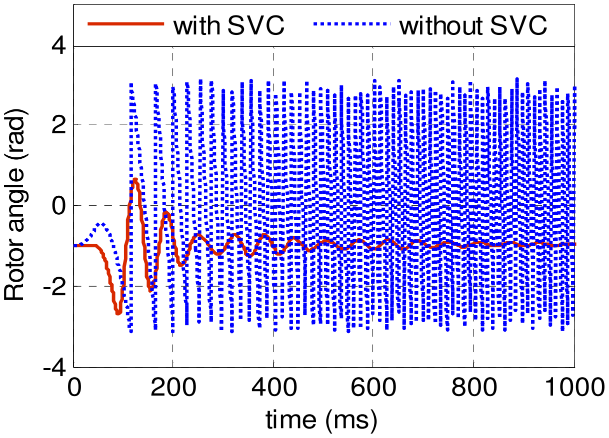

Figure 8: Rotor angle plot of Generator at Afam with and without SVC following a 3-phase fault

$$B_{SVC}(\alpha) = \left(B_L(\alpha) - \frac{1}{X_c}\right) \qquad (21)$$

The SVC is designed such that the TCR is switched off when the bus voltage falls below the reference voltage and turns on when it is above it. Therefore, the maximum reactive power consumed by the fixed capacitor (FC) and the thyristor controlled reactor (TCR) is given as:

$$Q_{SVC}^{Max} = B_{SVC}(\alpha) \times V^2{}_{SVC} \qquad (22)$$

while the minimum var consumption is obtained as:

$$Q_{SVC}^{\min} = -\frac{1}{X_C} V^2{}_{SVC} \qquad (23)$$

4. SIMULATION RESULTS AND DISCUSSION

Four scenarios (Case 1-Case 4) were created to have insight into the transient instability that may arise as a result of fault on any of the identified critical lines and also to determine the size and location of SVC (within the network) that would provide improvement to the security of the network. A three phase fault was created at the middle of each of the critical lines using step by step approach. The bus voltages in each of the scenarios were determined before and after the installation of SVC. Also, the CCT and the improvement in the transient stability (CCT) before and after the installation of SVC were determined. The location of the SVC that provides the best improvement to the overall stability of the system was determined by trial and error approach. The details of each of the scenarios are presented in the preceding subsection.

4.1 Case 1: Fault on Jebba - Osogbo Transmission Line

In this scenario, three-phase short circuit fault was created on Jebba–Osogbo transmission line using step by step technique. The voltage profiles of all the buses in the network before and after the installation of SVC are furnished in Tables 3 and 4 respectively. The voltage profile under this scenario (at CCT) reveals that the bus voltage of Kainji, Kaduna, Jos, Kano, Gombe, B/Kebbi and Jebba are 1.34p.u, 1.30p.u, 1.27p.u, 1.26p.u, 1.24p.u, 1.26p.u and 1.33p.u respectively. These are in absolute violation of the maximum allowed value of ±5% (i.e. 0.95-1.05p.u).

The generator at Jebba generating station is the most critically disturbed. This is expected as is the closest of the generators to the fault point. Installation of appropriately sized SVC at Osogbo restores the voltage values to allowable limit of 1.03p.u, 1.02p.u, 0.99p.u, 0.96p.u, 0.97p.u, 1.01p.u and 1.02p.u, respectively. The response of Jebba generator rotor angle to the disturbance with and without SVC is depicted in Figure 5.The result reveals that with SVC of size 124MVA in place, the critical clearing time was increased by 23.68%.

4.2 Case 2: Fault on Shiroro–Kaduna transmission line

In this scenario, 3-phase fault was created at the middle of Shiroro-Kaduna transmission line. The occurrence of faulton this overloaded tie line reduced the bus voltages at Kaduna, Jos, Kano and Gombe to zero indicating a black out of these areas. This is because the areas serviced by this transmission line were totally disconnected from the entire network since this is the only tie line linking these areas to the national grid. The fault also resulted into voltage violation at Osogbo, Ikeja-West and Egbin with recorded values of 1.11p.u, 1.07p.u and 1.07p.u, respectively. However, after the installation of appropriately sized SVC (73MVA) at Kaduna, all the bus voltages were restored back to allowable limit of±5%.. The voltages before and after the installation of SVC for all the buses under this scenario are depicted in Tables 3 and 4, respectively. The transient stability of the network indicated by the CCT was improved by 4.17% when SVC was installed on the line as revealed in Table 5. The rotor swing of the generator located at Shiroro station before and after the installation of the SVC is depicted in Figure 6.

4.3 Case 3: Fault on Benin- Sapele Transmission line

With the creation of 3-phase fault of any duration at the middle of Benin-Sapele transmission line, the generator located at Sapele was always losing synchronism. It was observed that this generator will always lose synchronism in the event of any 3-phase fault of any duration on the tie-line unless FACTS device is installed. The fault created on the line also resulted into violation of voltages at B/Kebbi, Gombe, Ikeja-West, Akangba, Egbin, Aja, Sapele GS, Aladja and Sapele with the voltage value of 0.92pu, 0.92pu, 0.94pu, 0.94pu, 0.94pu, 0.94pu, 1.52pu, 1.52pu and 1.52pu, respectively. The installation of 62MVA SVC restored all the bus voltages to allowable limit as shown in Table 4. The CCT before the installation of SVC could not be determined as it was always losing synchronism to fault of any duration. This shows that, synchronism will always be lost without SVC in an event of any contingency on the line. However, an installation of 62MVA SVC at Benin increased the CCT to 220ms indicating much improvement in transient stability. The rotor angle plot of the generator located at Sapele before and after the installation of SVC is depicted in Figure 7.

4.4 Case 4: Fault on Benin – Onitsha Transmission Line

Benin-Onitsha transmission line is a critical line that serves as the main link for power transfer to the eastern part of Nigeria. Applying three-phase fault on this line resulted into loss of synchronism of the generator at Afam station. This is because Benin-Onitsha is the only tie line supplying the region. Therefore, 3-phase fault of any duration without FACT device will always cause loss of synchronism of the generator at Afam stations. The fault resulted into voltage violation of most of the buses as depicted in Table 3. However, installation of SVC at Benin station restored all the bus voltages to acceptable limit of±5 ± % as furnished in Table 4. The installation of 110MVA SVC at Benin bus increased the CCTto120ms.The response of Afam generator rotor angle to 3 phase fault with and without SVC is depicted in Figure 8. The heavy oscillation without SVC was easily damped out in the presence of SVC.

Table 3: Case voltages and angles without SVC

BUS NO.	BUS NAME	CASE 1		CASE 2		CASE 3		CASE 4	
		Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)
1	B/Kebbi	1.26	154.49	1.05	-1.56	0.92	-6.84	1.02	-3.34
2	Kainji	1.34	159.32	1.12	3.26	0.98	-2.01	1.08	1.49
3	Jebba	1.33	159.26	1.11	3.15	0.97	-2.17	1.08	1.37
4	Kainji GS	1.35	160.05	1.13	4.33	0.99	-0.61	1.10	2.62
5	Jebba GS	1.34	160.00	1.13	4.23	0.99	-0.75	1.10	2.52
6	Jebba TS	1.33	159.26	1.11	3.15	0.97	-2.17	1.08	1.37
7	Osogbo	0.88	-4.97	1.11	2.70	0.97	-2.49	1.07	1.19

BUS NO.	BUS NAME	CASE 1		CASE 2		CASE 3		CASE 4	
		Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)
8	Shiroro	1.31	157.84	1.15	5.24	0.97	-2.36	1.07	0.66
9	Shiroro GS	1.32	158.62	1.16	6.27	0.99	-0.93	1.09	1.83
10	Kaduna	1.30	157.37	0.00	-135.00	0.97	-2.82	1.07	0.19
11	Ajaokuta	0.92	-3.67	1.09	0.69	0.95	-3.91	1.09	1.99
12	Kano	1.26	155.46	0.00	135.00	0.94	-4.74	1.04	-1.72
13	Jos	1.27	155.93	0.00	135.00	0.94	-4.26	1.04	-1.25
14	Gombe	1.24	154.26	0.00	135.00	0.92	-5.94	1.02	-2.92
15	Benin	0.92	-3.45	1.09	0.91	0.96	-3.69	1.09	2.21
16	Onitsha	0.91	-4.67	1.07	-0.76	0.94	-4.99	0.71	-106.20
17	New Haven	0.91	-4.94	1.06	-1.03	0.94	-5.26	0.71	-106.46
18	Aiyede	0.87	-5.00	1.09	1.80	0.95	-3.05	1.06	0.71
19	Alaoji	0.92	-4.15	1.07	-0.77	0.95	-4.55	0.73	-104.32
20	Ikeja-West	0.88	-4.25	1.07	1.18	0.94	-3.14	1.05	0.75
21	Akangba	0.88	-4.26	1.07	1.18	0.94	-3.15	1.05	0.75
22	Egbin	0.88	-3.91	1.07	1.38	0.94	-2.85	1.05	0.96
23	Egbin GS	0.90	-1.92	1.08	2.75	0.96	-1.08	1.07	2.37
24	Aja	0.88	-3.92	1.07	1.38	0.94	-2.86	1.05	0.95
25	Sapele GS	0.94	-2.24	1.10	1.79	1.52	53.39	1.10	3.09
26	Aladja	0.93	-3.09	1.09	1.15	1.52	53.11	1.10	2.45
27	Delta GS	0.95	-1.52	1.11	2.30	0.99	-1.41	1.11	3.60
28	Afam GS	0.94	-2.59	1.09	0.41	0.97	-3.05	0.75	-101.84
29	Afam	0.92	-4.12	1.07	-0.75	0.95	-4.53	0.73	-104.27
30	Delta	0.93	-3.04	1.10	1.19	0.97	-2.82	1.10	2.49
31	Sapele	0.93	-3.28	1.09	1.03	1.52	53.18	1.09	2.33

Table 4: Case voltages and angles with SVC

BUS No.	BUS NAME	CASE 1		CASE 2		CASE 3		CASE 4	
		Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)
1	B/Kebbi	1.01	-4.26	1.01	-1.56	1.03	-3.34	1.01	-6.84
2	Kainji	1.03	-3.51	1.02	3.26	1.02	1.49	1.02	-2.01
3	Jebba	1.02	-1.32	1.01	-2.17	1.02	1.37	1.01	-2.45
4	Kainji GS	1.01	2.92	1.02	-0.61	1.03	-2.42	1.02	-5.76
5	Jebba GS	1.00	1.24	1.01	-0.75	1.03	-5.52	1.02	-1.03
6	Jebba TS	1.02	-3.09	1.01	-2.17	1.02	-3.37	1.01	-3.15
7	Osogbo	0.98	-1.52	1.02	-2.49	1.01	-5.19	0.99	2.70
8	Shiroro	1.01	7.84	1.00	5.24	1.01	-1.34	1.00	-2.36
9	Shiroro GS	1.00	0.62	1.00	0.27	1.02	-0.83	1.01	-10.93
10	Kaduna	1.02	-7.37	0.98	0.75	1.01	0.19	0.99	-2.82
11	Ajaokuta	0.98	-2.67	0.97	0.96	1.00	1.99	0.97	-3.91
12	Kano	0.96	-15.46	0.99	2.37	1.00	-1.72	0.98	-4.74
13	Jos	0.99	-4.25	0.98	0.95	1.01	-1.25	0.97	-4.26
14	Gombe	0.97	-4.26	0.97	-2.09	0.99	-2.92	0.96	-5.94
15	Benin	0.98	-8.45	0.99	-2.45	0.98	2.21	0.98	-3.69
16	Onitsha	0.96	-4.99	0.97	-5.76	0.99	-10.20	0.96	-4.99
17	New Haven	0.96	25.93	0.97	-1.03	0.98	-46.32	0.95	-5.26
18	Aiyede	0.97	-2.59	0.99	1.80	0.98	-8.73	0.97	-3.05
19	Alaoji	1.01	-4.12	0.98	-0.27	1.00	-24.32	0.98	-3.32
20	Ikeja-West	0.98	-3.04	0.99	-2.18	0.99	-18.58	0.97	7.84
21	Akangba	0.97	-3.28	0.98	-1.48	0.98	-4.55	0.96	0.62
22	Egbin	1.02	-3.43	1.03	2.48	1.03	-3.14	1.02	-7.37
23	Egbin GS	1.03	-4.67	1.03	0.75	1.03	-3.15	1.02	12.35
24	Aja	1.01	-4.94	1.01	1.38	1.02	-2.65	1.01	-7.81
25	Sapele GS	1.02	-15.13	1.02	1.79	1.03	-1.08	1.03	53.39
26	Aladja	1.02	-4.15	1.01	1.15	1.01	-2.86	1.01	53.11

BUS No.	BUS NAME	CASE 1		CASE 2		CASE 3		CASE 4	
		Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)	Voltage (p.u)	Angle (deg.)
27	Delta GS	1.01	3.15	1.03	-1.41	1.03	3.60	1.02	-3.51
28	Afam GS	1.01	4.33	1.02	-3.05	1.01	-1.84	1.01	-1.32
29	Afam	1.01	4.23	1.02	-4.53	1.01	-1.25	1.01	-5.52
30	Delta	1.00	-3.15	1.01	-2.82	1.01	2.44	1.00	-3.37
31	Sapele	1.00	2.70	1.00	-3.01	1.00	4.31	1.00	53.18

Table 5: Critical clearing time with and without SVC when a 3-phase fault occurs on the critical line

Case No.	Line Fault	% Loading	CCT without SVC (ms)	CCT with SVC (ms)	SVC Sizing (MVar)	Best location of SVC	% Improvement
1.	Jebba -Osogbo	120	380	470	124	Osogbo	23.68
2.	Shiroro-Kaduna	100	480	500	73	Kaduna	4.17
3.	Benin-Sapele	123	-	220	62	Benin	much
4.	Benin-Onitsha	118	-	120	110	Benin	much

Values cannot be determined

5. CONCLUSION

The assessment of Nigerian 330kV transient stability has been performed with a view to improve on the stability of the network with appropriately sized and located SVC. The result shows that Jebba- Osogbo, Shiroro-Kaduna, Benin-Sapele and Benin-Onitsha are the critical lines within the network that can excite instability in the network. At steady state, the network bus voltages are within acceptable $\pm 5\%$ voltage limit. However, the bus voltages of some of the buses within the network were expectedly violated when 3-phase fault were applied at the middle of these critical lines. Installation of appropriately sized SVC with the values of 124MVA, 73MVA, 62MVA and 110MVA at Oshogbo, Kaduna and Benin maintained the bus voltage within acceptable limit in event of 3-phase fault. The critical clearing time of the acute generators when 3-phase fault occurs on Jebba-Oshogbo and Shiroro-Kaduna increases from 380ms, 480ms to 470ms and 500ms, respectively with the installation of the SVC. The generators located in Sapele and Afam station will always lose synchronism in an even of 3-phase fault on Benin-Sapele and Benin-Onitsha transmission line. However, the CCT was increased to 220ms and 120ms, respectively with installation of SVC at Benin station.

This paper may be useful to the Nigerian electricity utility companies for proper planning of Nigerian national grid and also in the formulation of policy on improving Nigerian Power system. Future research will focus on development of indices that will aid the sizing and location of SVC within the Nigerian 330kV power system network with the aim of improving the transient stability of the network.

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APPENDIX

Table 6: Transmission Line Data for 330kV Nigeria Power System

LINE NO.	FROM BUS i	TO BUS J	LINE PARAMETERS (P.U)				
			R	X	B	TAP	PHASE
1	1	2	0.01218	0.09163	1.0269		
2	2	3	0.00159	0.01197	0.5366		
3	2	4	0	0.01351	0	1	0
4	3	6	0.00016	0.00118	0.053		
5	3	7	0.00206	0.01547	1.56		
6	3	8	0.00480	0.03606	1.6165		
7	5	6	0	0.01932	0	1	0
8	7	15	0.00987	0.07419	0.8315		
9	7	18	0.00412	0.03098	0.3472		
10	7	20	0.01163	0.08750	0.9805		
11	8	9	0	0.01638	0	1	0
12	8	10	0.00189	0.01419	0.636		
13	10	12	0.00904	0.06799	0.7619		
14	10	13	0.00774	0.05832	0.6526		
15	11	15	0.00766	0.05764	0.646		
16	13	14	0.01042	0.07833	0.8778		
17	15	16	0.00538	0.04050	0.4538		
18	15	20	0.00550	0.04139	1.885		
19	15	30	0.00287	0.02158	0.2418		
20	15	31	0.00098	0.00739	0.3313		
21	16	17	0.00377	0.02838	0.318		
22	16	19	0.00605	0.04552	0.5101		
23	18	20	0.00538	0.04050	0.454		
24	19	29	0.00049	0.00369	0.1656		
25	20	21	0.00036	0.00266	0.119		
26	20	22	0.00122	0.00916	0.4108		
27	22	23	0	0.00648	0	1	0
28	22	24	0.00028	0.00207	0.0928		
29	25	31	0	0.01204	0	1	0
30	26	30	0.00102	0.00769	0.08613		
31	26	31	0.00248	0.01862	0.2087		
32	27	30	0	0.01333	0	1	0
33	28	29	0	0.01422	0	1	0

Table 7: Generator Data for 330kV Nigeria Power System

Gen.	Names	MVA	H	x_d	x'_d	x''_d	x_q	x'_q	x''_q	T'_{d0}	T''_{d0}	T'_{q0}	T''_{q0}	x_l	R
G1	Kainji	450	3.34	0.75	0.28	0.21	0.53	-	0.21	6.0	0.04	-	0.16	0.16	0.004
G2	Jebba	600	3.39	0.65	0.26	0.24	0.44	-	0.24	5.2	0.06	-	0.24	0.14	0.0037
G3	Egbin	1500	3.09	1.87	0.262	0.23	1.87	0.45	0.22	7.1	0.063	1.0	0.11	0.18	0.004
G4	Shiroro	700	3.24	0.80	0.30	0.2	0.49	-	0.24	5.57	0.05	-	0.34	0.16	0.004
G5	Sapele	440	8.91	2.17	0.25	0.18	1.92	-	0.18	8.8	0.05	-	0.20	0.13	0.004
G6	Delta	550	6.70	2.16	0.234	0.17	2.16	-	0.16	8.6	0.05	-	0.20	0.12	0.002
G7	Afam	330	9.01	2.09	0.20	0.15	1.89	-	0.15	6.93	0.05	-	0.20	0.11	0.003