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RESEARCH ARTICLE

Development of a Model for Improving Power System Voltage Stability in Nigerian 330kv 48-Bus Network During Loss of Equivalent Network

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ABSTRACT

This research work aims at improving the voltage stability of the Nigerian 330KV Power network using Hybrid devices – Unified Power Flow Controller (UPFC) and Static Var Compensator (SVC) – of FACTS devices. The electric power system voltage stability is being threatened by disturbances in different ways such that the system becomes unstable. The threat which emerges as loss of generation to switching, change in loads, and fault conditions creates an adverse effect on Nigerian power system. The undesirable impact of the disturbances can be so severe that both the utility providers and consumers suffer seriously. The instability on the network causes frequent outages cascaded blackouts and sometimes voltage collapse. This increases production cost for industrial consumers and reduces national development. Unfortunately, the attempts made, to resolve this problem has not given a maximum result. Line and Bus data used as input data were collected from Transmission Company of Nigeria. Load flow was performed first as a straw test to know if the system was healthy or not, and consequently continuation power flow was also run to determine the critical buses that need to be compensated. The models of UPFC and SVC were developed. An equivalent network of the 48-bus 330KV network was created. Artificial neural network controllers were created and trained to optimize the compensating capacity of the hybrid device. To enhance the voltage stability of the Nigerian 330KV 48-bus network during the contingency of loss of equivalent on the line. The hybrid device (UPFC-SVC) was connected to the network and simulated and the result showed that it improved the power system stability by 25% as against when the system was not compensated.

***Keywords**: Improving Power System Voltage Stability; Nigerian 330kv 48-Bus Network; During Loss of Equivalent Network*

Introduction

Quality and stable electricity supply in any nation brings about national development. Nigeria as a case study lacks frequent supply of electricity and so it has multidimensional problems. For instance, looking at the World Bank estimated electricity generated capacity in Nigeria and other countries, it noted that Nigeria with a capacity of 8,644MW uses only about 3,718MW to service a population of over 180 million people (World Bank, 2015). This insufficiency in supply affects the economic situation of the country.

One of the major issues facing competitive energy market is that one or several disturbances may affect reactive power generated, thereby leading to voltage instability. The need for a fast-working electrical system has given rise to better electrical Technological innovations on transmission lines through the use of solid-state devices. One can simply identify the continued use of certain aged equipment, vandalizing of cables, and other electrical gargets as a contributor to power inefficiency in Nigeria. Consequently, continued divert of fund meant for the improvement of power system affect the growth of power system in Nigeria. However, the solid-state devices are referred to as FACTS meaning not rigid irregular current transmission system. The FACTS device enhances electric power system stability. These entire devices have gone a long way in solving electric power issues like that of voltage unsteadiness, energy flow control problems, imbalances between reactive power and active power flow. These FACTS are based on power electronics voltage source which is capable of generating internally and absorbing reactive power without the use of AC capacitors or reactors. These devices provide independent control for active and reactive energy flow as they facilitate their power compensation. The main objective of FACTS devices is to enhance power transmission capacity, energy control, power steadiness enhancement and power system stability enhancement. The idea of FACTS was initiated by N. G. Hingorani (1988). Since then, different FACTS controllers have come into play in the area of transmission voltage stability. These FACTS controller is dependent on power supply converters and they include devices like Static Var Compensator (SVC),

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Static synchronous compensator (STATCOM), Thyristor controlled series compensator (TCSC), Static synchronous series compensator (SSSC) and unified power flow controller (UPFC). The concept UPFC was described by L. Gyngyi of Westinghouse (1995). UPFC among all the FACTS devices is more versatile and efficient in controlling the transmitted power by simply replacing the transmitted voltage magnitude, impedance and the phase angle. In this thesis, we shall integrate SVC and UPFC models to achieve a better result in enhancing energy system voltage steadiness. The static-Var compensator does not have any considerable moving parts but has internal switchgear. Electric power system is brought closer to unity power factor by an automated impedance matching device designed for it. This is used in two main situations (1). It is linked to power system to control the transmission energy (Transmission SVC). (2). It is linked near huge industrial loads to improve power quality (Industrial SVC). If the power system reactive load is capacitive (leading), the SVC will use thyristor-controlled reactors to consume VARS from the system thereby lowering the system voltage. Under industrial (lagging) conditions, the capacitor banks are automatically switched on, thus providing high system voltage.

There is need to do a proper load flow analysis so as to determine the system's stability and the weakest buses in the grid. This analysis will bring to bear instability problems in the buses, instability of voltage in electric power system denotes a condition involving loss of synchronism or falling out of step. Instability of voltage in electric power system brings about voltage collapse especially when the post disturbance equilibrium voltage close to the load is less than acceptable limits.

Power System Stability

Electric power system steadiness is referred to as an ability of an electric power system to maintain equilibrium balance within the system after an interruption has occurred without loss of bounded variables. [Kumar, 2004]
Power system stability is an embodiment of the regular stability, transient steadiness dynamic steadiness. The steadiness of a system is the ability of that system to return back to its steady state after being lured into disorder. Power system is a multifaceted dynamic system that comprises of both linear and non-linear subsystems which is always subjected to disturbances. Looking at its physical presentation and its mode of instability, power system can be classified into three: Rotor Angle steadiness, voltage steadiness and frequency steadiness

Voltage Stability

Voltage stability is defined as the ability of power system to maintain steady voltage at all buses in the system after being subjected to disturbances. Often times disturbances create imbalance in power system either by shortage of reactive power supply or excessive supply of it, thereby making the system impossible to maintain a steadiness involving load demand and load supply, in the event of disturbance, the action leads to instability in the system. When this happens, there may be loss of load in some areas causing tripping of transmission lines and other elements by their protective system resulting in voltage collapse or blackout (Kundur et al, 2004). Voltage collapse is defined as a process by which the voltage instability provides advantages of a very low voltage profile in the essential part of the system. Voltage stability is classified into two categories namely; nce voltage stability involves large disturbances such as system faults, loss of load or loss of generation for determination of this kind of stability. A system is said to have small-disturbance voltage stability, if the voltage near loads does not change or if the voltage remains close to the pre-disturbance value. From the above 2 and 3 definitions of power system and voltage stabilities, one observes that the system maintains a stable voltage in all bus after being subjected to contingencies of fault condition, change in load or generator losses.

Methodology

This Methodology describes an approach, towards achieving successful voltage stability, in electric power system of Nigerian 330KV 48- bus network. In this research work two devices, namely UPFC and SVC were combined to achieve, more robust voltage power stability. But before this was applied on the line, it was absolutely important to first and foremost identify the weak buses and lines with poor voltage and high losses, by running a load flow on the network and consequently, a continuation power flow analysis is run in other to overcome any convergence issues that may occur at critical points. Continuation power flow helps to find solutions to convergence issues at critical point, at points approaching critical point and points beyond yet close to critical point. This discovery provides accurate assessment of stability margin, whether the system stability critical point is measuring from either stable or unstable domain. Having discovered from the network the buses of extremely low voltage and lines of high losses that need to be compensated, it is important to employ the use of hybrid technology – UPFC and SVC to compensate them.

There is need to design a monitoring tool Neural network controller to control the modeled UPFC and SVC so as to maintain a balance between the reactive and active power for a maximum performance and hence give a better result. The running of load flow analysis on 330KV 48-bus system as a straw test and continuation power flow on the network using MATLAB/SIMULINK and PSAT is presented. Matlab tools will make the computation and graph plotting on Excel faster and easy, considering large number of buses-48 bus network involved.

In the developed hybrid technology – Unified power flow controller (UPFC) and Static Var compensator (SVC), Line and Bus data used as input data were collected from Transmission company of Nigeria. Load flow was performed first as a straw test to know if the system has problem or not and consequently continuation power flow was also run to determine the critical buses that need to be compensated. The simulation of the system result on the 330KV 48-bus Nigeria network showed that the hybrid technology improved the buses that had unacceptable voltage mark of 0.95 pu to acceptable voltage level. The result of the developed hybrid measured a maximum power loss of 0.094% which was much lower than the result of the simulation of Jalla (2016) on UPFC System stability that measured 0.125.

Principle of Operation of Unified Power Flow controller (UPFC)

The unified Power Flow Controller (UPFC) is basically a combination of Static Synchronous compensator STATCOM and Static Synchronous Series Compensator (SSSC). The STATCOM is connected to shunt transformer and the SSSC is connected to series transformer respectively on transmission line. The structure of UPFC contains also a "back-to-back AC to DC voltage source converters operated from a common DC link capacitor, first converter (CONV1) is connected in shunt and the second one (CONV2) in series with the line. The shunt converter is primarily used to provide active power demand of the series converter through a common DC link. Converter 1 can also generate or absorb reactive power, if it is desired, and thereby provide independent shunt reactive compensation for the line. Converter 2 provides the main function of the UPFC by injecting a voltage with controllable magnitude and phase angle in series with the line via a voltage source, The UPFC injection model is derived enabling three parameters to be simultaneously controlled. They are namely the shunt reactive power, Qconv1, and the magnitude, r, and the angle, of injected series voltage $\overline{V}se$

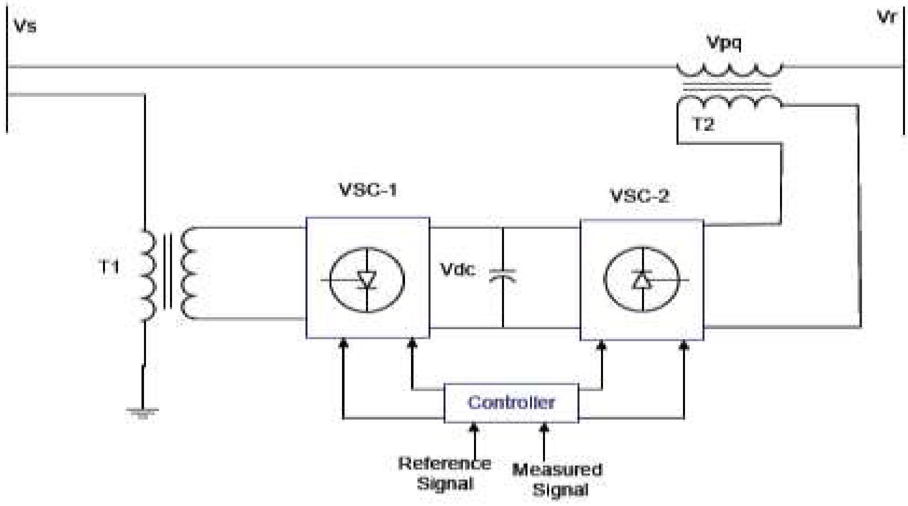

Figure 1: Unified power flow controller (UPFC) Schematic Diagrams

The shunt converter compensates real power drawn, which is supplied by series converters. Both converters independently exchange connected transformers. It is observed that the transmission of real power in existing transmission line is highly improved with the presence of UPFC under dynamic condition, whereas real power flow in line without UPFC is decreased. This is also clear that after clearing of fault the oscillations in real power is also damped with the UPFC and system recover its pre-fault conditions faster.

Mathematical Modeling of Unified Power Flow Controller (UPFC)

Unified power flow controller (UPFC) is facts device capable of controlling transmission line power flows, voltage magnitudes and phase angle, it is important therefore to show mathematically how it is in the power system. The model is based on a power balance technique similar to the one used in the development of a STATCOM model, i.e.

$$P_{ac} = P_{dc} + P_{losses} \qquad (1)$$

The three-phase instantaneous power flowing into the shunt converter from the ac bus, neglecting transformer losses and assuming fundamental frequency and balanced conditions can be represented by

$$P_{sh=} 3V_k I_{sh} \cos(\delta_k - \theta_{sh}) \qquad (2)$$

Where: $V_k - \delta_k$

Is the rms-phasor of the sinusoidal sending-end voltage V_{ic} and $I_{sh} < \theta_{sh}$ is the rms phasor of the converter's sinusoidal current, this phase power is the same as the average power for a balanced system.

Where:

$I_{i<}\theta_l$ is the rms phasor value of the ac line current $I_{l,and}$ $V < \delta =$

$V_K < \delta_k$ - $V_m < \delta_m$ is the rms phasor of the series converter's output voltage V for the serial branch.

$$P_{Se} = 3V_{I,} \cos(\delta - \theta_1) \qquad (3)$$

It is important to note here that implementation of the unified power flow controller (UPFC), the converter sinusoidal voltage V_{ish} is typically referred to the controller shunt or sending ends bus voltage V_{kj} i.e.

$$V_k = \sqrt{2V_k} \sin(w_t \delta_k)$$

$$V_{ish} = \sqrt{2V_{ish}} \sin(wt + \underbrace{\delta_k + \Delta\propto}_{\propto}) \qquad (4)$$

For the series phasor voltage, the controls are designed looking at the receiving end bus voltage

$V_{i,}$ i.e.

$$V_i = \sqrt{2V_i} \sin(wt + \delta_t)$$

$$V_{ise} = \sqrt{2V_{ise}} \sin(wt + \underbrace{\delta_c + \Delta\beta}_{\beta}) \qquad (5)$$

However, the AC losses which are the effect of switching losses can be approximately modeled using serial resistor R_{sh} and R_{se} in both converters and d_c losses may be represented with a resistor.

$R_C = {}^{I}/_{G_C}$ Connected in shunt with the dc capacitor.

The UPFC power balance equations, assuming real power flow from the shunt converter to the series converter may be given thus:

$$P_{sh} - P_{Se} = V_{dc} \underbrace{\left(C \frac{dVdc}{dt}\right)}_{Idc} + V_{dc}^2 G_C + 3\,((a_{sh} Ish^2) R_{sh} + 3\,((a_{se} I_{se})^2 R_{se} \qquad (6)$$

Where a_{sh} and a_{sk} are the shunt and series transformer voltage ratios and V_{dc} is the average d_c capacitor voltage.

$\therefore UPFC\ d_c$ Voltage V_{dc} in the transcient stability model can be defined by the following equation non-linear differential equation.

$$\frac{dv_{dc}}{dt} = 3\ \frac{V_k I_{sh}}{CV_{dc}}\cos(\delta_k - \theta_{sh})\text{- }3\ \frac{V_I I_{sh}}{CV_{dc}}\cos(\delta - \theta_1) - \frac{G_c}{C}V_{dc}\text{- }3\frac{as_h^2 I_{sh}^2}{CVd_c}R_{sh}\text{ -}3\frac{as_h^2 I_{sh}^2}{CVd_c}R_{se} \tag{7}$$

This equation (4.7) can be simplified if the ac losses represented by $R_{sh}\ and\ R_{se}$ are neglected but it introduces error in the model.

Especially when the ac switching losses are high. In this case the equation can therefore be transformed into:

$$\frac{dv_{dc}}{dt} = 3\ \frac{V_k K_{sh}}{C_{ash}\,X_{se}}\sin(\delta_k - \propto)\ \text{- }3\ \frac{V_k K_{sh}}{C_{ash}\,X_{se}}\sin(\delta_c - \beta) - \frac{G_c}{C}V_{dc} \tag{8}$$

Here, K_{sh} and K_{se} are defined based on a Fourier analysis of the converters output voltage V_{ish} and $V_{ise,}$ respectively. V_{ish} and V_{ise} are the corresponding rms value, these can be expressed as:

$$V_{ish} > \frac{1}{2\sqrt{2}}M_{sh}V_{dc}\ = K_{sh}V_{dc} \tag{9}$$

$$V_{ish=}\ \frac{1}{2\sqrt{2}}M_{se}V_{dc}\ = K_{se}V_{dc} \tag{10}$$

Static VAR Compensator (SVC)

The single-phase Static Var compensator model (SVC) shown in fig 2 below belongs to the family of flexible AC transmission system FACTS devices. It regulates voltage, power factor, harmonics and it stabilizes the system. It is a set of electrical devices for providing fast acting reactive power on high voltage electricity transmission network; SVC is connected in parallel with the load to be compensated. The reactive power being provided is proportional to the system supply voltage. Through the use of thyristor-controlled reactors, SVC generates fast response reactive power and passive filter capacitor bank generates harmonic current. The capacitor bank is fine tuned for not only reducing harmonics generated by the load but also from the system itself. Thyristors can be tuned ON once per cycle. The SVC is an automated impedance matching device designed to bring the system closer to unity power factor. The SVC'S are used in two main ways. It is connected to the power system to regulate the transmission voltage (transmission SVC), secondly it is connected near large industrial loads to improve power quality (industrial SVC). When the power system reactive power is capacitive SVC will use the thyristor-controlled reactors to consume VARS from the system and the system voltage will be lowered, but if it is inductive (lagging), the capacitor bank will automatically be switched on, thereby proving a higher system voltage.

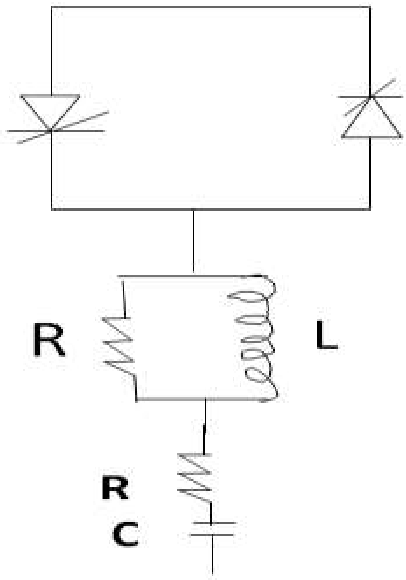

Figure 2: System design of SVC

Mathematical Model of SVC Newton Raphson Power Flows

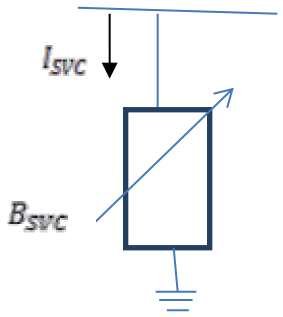

Figure 3: variable shunt Susceptance

Looking at the Figure above the current drawn by the SVC is given by (1) $j\beta_{SVC}$

$$I_{\mathrm{SVC}} = \mathrm{J}V_k \quad (11)$$

And the reactive power drawn by the SVC which is the reactive power injected at bask, is given by

$$Q_{SVC} = Q_{K-V_K^2\beta_{SVC}} \quad (12)$$

Linearized equation of the SVC is given as:

$$\begin{bmatrix}\Delta P_k\\ \Delta Q_k\end{bmatrix}\begin{bmatrix}0 & 0\\ 0 & Q_K\end{bmatrix}\begin{bmatrix}\Delta\emptyset_k\\ \Delta BB_{SVC}/B_{SVC}\end{bmatrix}^{(i)}$$

Where the equivalent susceiptanceB_{SVC} is taken to be the state variable. At the end of iterations the variable shunt susceptance B_{SVC} is updated in the form

$$\beta_{SVC}^{(c)} = \beta_{SVC}^{I-11} + \left(\frac{\Delta BSVC}{BSVC}\right)B_{SVC}^{(i=q)} \quad (13)$$

The positive sequence susceptance of the S_{VCC} is given as

$$Q_k = \frac{-V_{1-}^2}{X_cL_l}(X_l - \frac{X_c}{\pi}[2(\pi - \alpha SVC) + \sin 2\,\alpha SVC] \quad (14)$$

Where αSVC is the firing angle of the SVC form equations the linearized SVC equations is given as:

$$\begin{bmatrix}\Delta P_k\\ \Delta Q_k\end{bmatrix}^{(i)} = \begin{bmatrix}0 & \frac{2V_k^2}{\pi X_L}\\ 0 & \end{bmatrix}(cos(2\alpha SVC)^0 - 1]\begin{bmatrix}\Delta\theta_K\\ \Delta\alpha_{svc}\end{bmatrix}^{(i)} \quad (15)$$

At the end of iteration us, the variable firing angle $\propto_{SVC}$ is update thus:

$$\propto_{SVC}^{(i)} = \propto_{SVC}^{(i=1)} + \Delta\propto_{SVC}^{(i=1)} \quad (16)$$

The new SVC susceptance, B_{SVC} can be determined by

$$B_{SVC} = X_e - \frac{X_c[2(\pi - \alpha SVC) + Sin\,(2\alpha SVC)]}{\frac{\pi}{X_cX_c}} \quad (17)$$

Note that the equivalent susceptacne profile of SVC as a function of firing angle does not show the discontinuities as B_{SVC} vain continuously and smoothly in both inductive and capacitive operating regions.

There is an existing Newton Raphson power flow program where an observation of the voltage controlling capacity of SVC model in an IEEE 14- buses interconnected power system network consisting of 14 buses, 20 transmission line diagram of the network below:

Data collected from IEEE, 14 bus test cases are, generation data, load data transmission data and line data this data are used with Newton Raphson based Matlab program.

Development of ANN controller for UPFC and SVC

The ANN controller models for the compensating devices (UPFC and SVC) were developed to make the compensating intelligent so as to obtain optimum reactive power compensation at the weak buses for optimum performance of the System. The neural network models are able to sense the voltage level at the weakest bus and use this information to generate the right firing pulses for the STATCOM bridges.

In order to do this, an equivalent 3-phase 48 bus network was modeled in Simulink workspace since the developed UPFC model is 3-phase. The equivalent three phase model of the test network is first simulated with UPFC and SVC not connected to the network. The obtained three phase bus voltage and current formed the input to the UPFC ANN controller. UPFC only was then connected to the same network and firing pulses were adjusted to achieve desired voltage level of 1.0pu. The firing pulses that gave the desired voltage level formed the target for the UPFC ANN controller. The obtained input and target data were then loaded into the MATLAB workspace. The ANN development interface was then opened in simulink. The ANN fitting application in the interface is used to access the input and target data in the work space. The fitting application is used to create and train the UPFC ANN controller. LevemburgMacquet back propagation training algorithm was used to train the ANN. A total of 402 data set for both input and target data were used for the training. After a successful training, the developed ANN controller was then deployed into a simulink model for use during simulation for the optimum control of the UPFC for excellent performance. The development of the SVC ANN controller followed the same procedure described above for UPFC ANN controller.

Evaluation of System Performance

The hybrid system (UPFC and SVC) performance in improving the voltage profile stability was evaluated under the assessment of improvement of the network on the imposition of the loss of the equivalent network when the hybrid was connected to the network in comparison with when no compensating device was connected. Let the compensating voltage profile be Vch and non compensating voltage be Vcn respectively, then voltage profile system margin is represented as

$$VPSM = \frac{Vch - Vcn}{Vcn} \tag{18}$$

Simulation, Results and Discussion

The developed single line 330KV 48-bus network model in MATLAB/ PSAT SIMULINK is shown in appendix 1. The bus and line data extracted from Transmission Company of Nigeria (TCN) was loaded into PSAT for running continuation power flow in other to identify the weakest bus in the network to be compensated. The weakest bus identified in the network is Yola; 0.478pu. The loss of equivalent network was simulated without compensating device connection to Yola bus as shown in appendix 2 and later simulated with the connection of the compensating device UPFC-SVC. The loss of equivalent networkis shown in appendix 3. The waveform result of the simulation when no compensating device was connected is shown in figure 4 and the waveform result when the compensating device UPFC-SVC was connected to the network is shown in figure 5

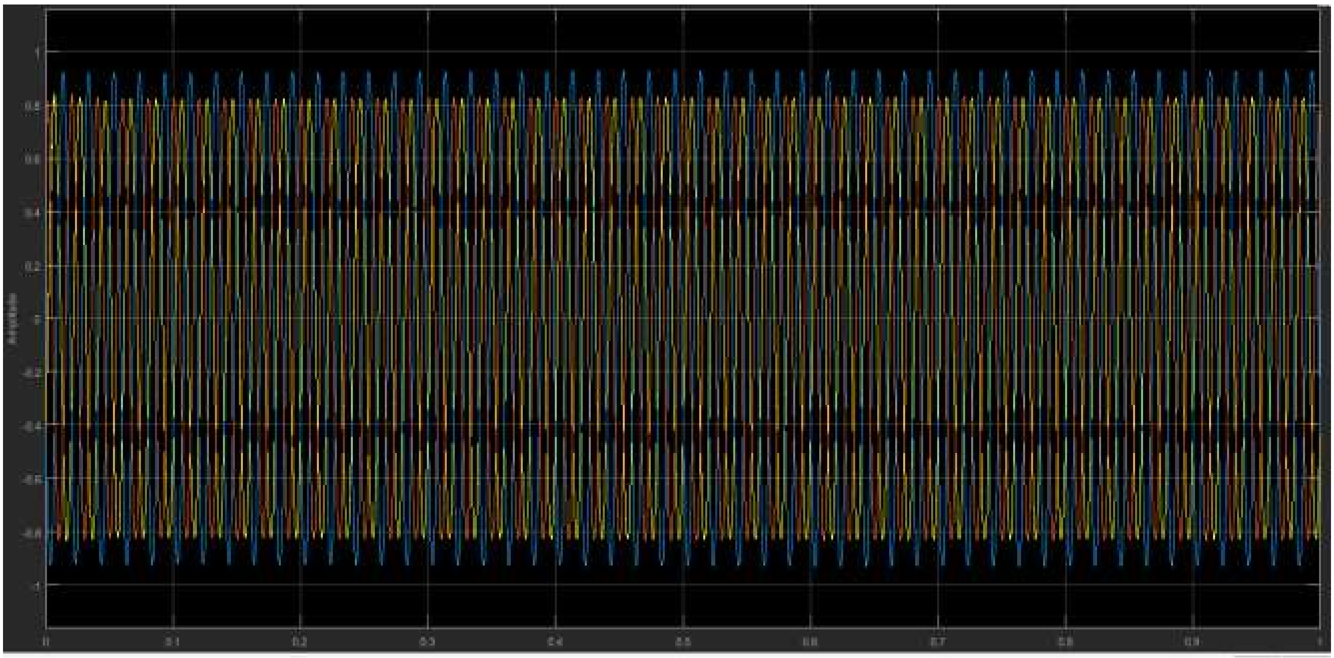

Figure 4: Waveform for loss of equivalent network scenario with no compensating device connected

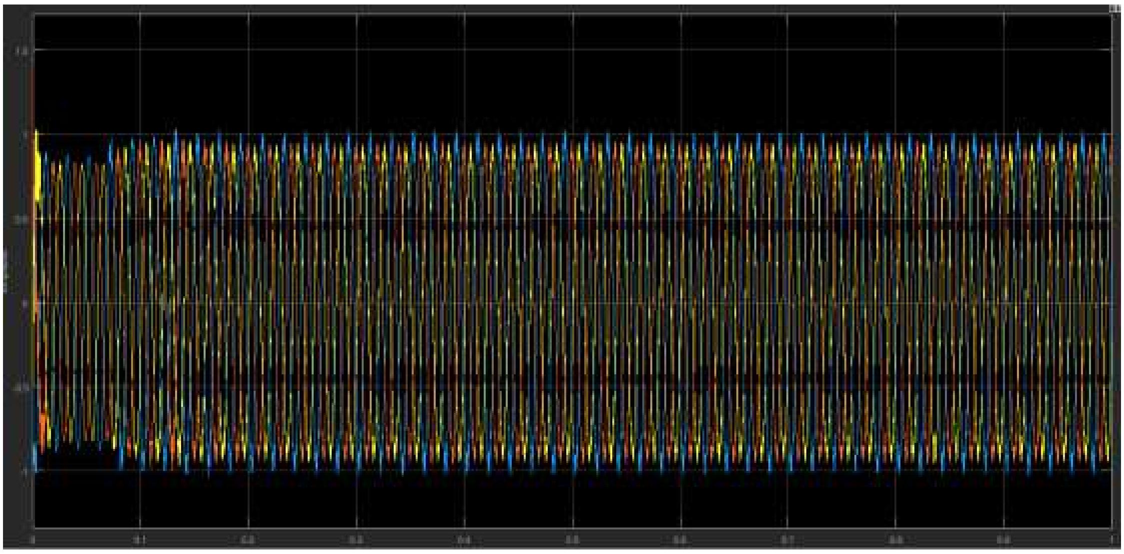

Figure 5: Waveform for loss of equivalent network with the hybrid (UPFC and SVC) connected

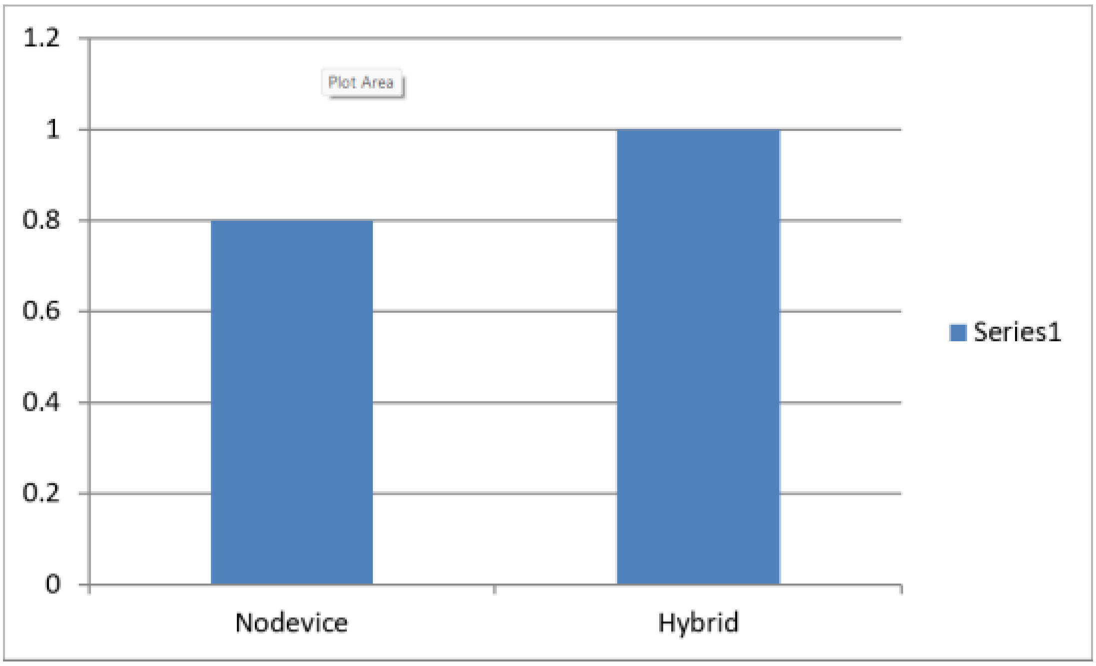

Figure 6: Bar chat graph showing the peak voltage profiles (with and without devices) on network simulation under the contingency of loss of equivalent network to compensate Yola bus.

Table 1: Voltage profile of the weakest bus, Yola at critical point during loss of equivalent network

Contingency	**No Device**	**UPFC-SVC**
Loss of Equivalent Network	**0.8**	**1.00**

VPSM = (1-0.8)/0.8

= 0.2/0.8

= 0.25

From the calculated VPSM and the Table 1 and figure 6 above one sees that the hybrid device UPFC-SVC compensated Yola to acceptable voltage mark of 1.00pu at the percentage increase of 25%.

Conclusion and Recommendation

It is concluded from the results recorded that the hybrid technology UPFC-SVC is good for enhancement of transmission line voltage profile, therefore it is recommended to be installed on Transmission lines to improve the vulnerable voltages. ANN controllers have been found to be a good catalyst for aiding FACTS devices in absorbing or generating voltages where necessary.

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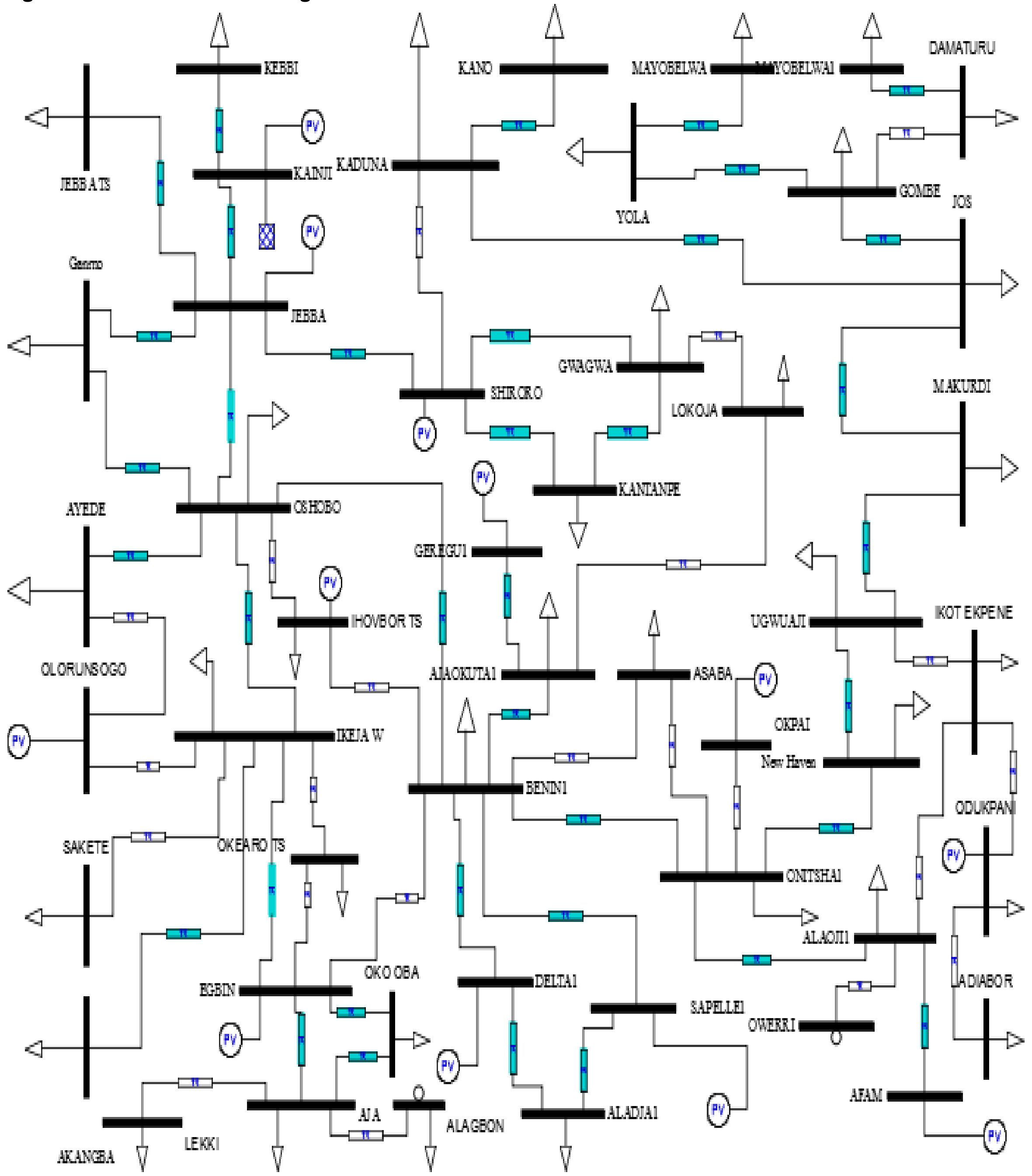
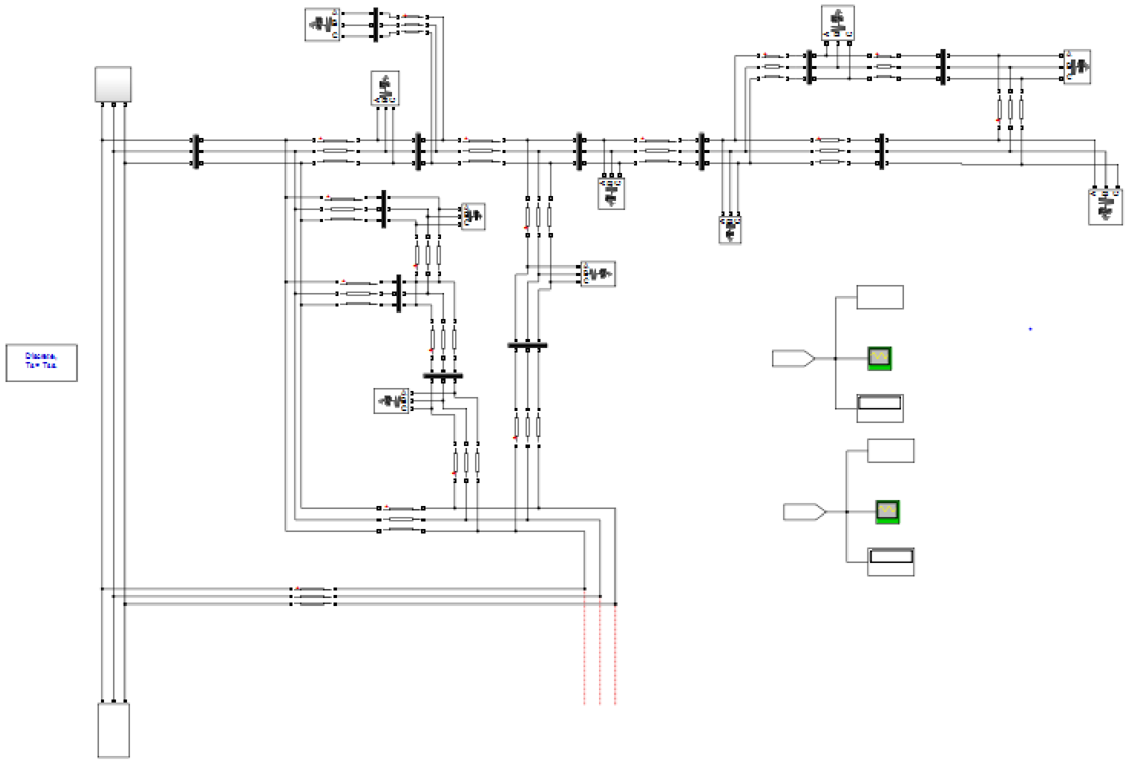
APPENDIX 1
Single line Simulink Model of Nigerian 330KV 48-bus



APPENDIX 2
Loss of Equivalent Network with No Device connection



APPENDIX 3
Loss of Equivalent Network with hybrid device connected