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Improving the Voltage Stability of the Nigeria 44- Bus 330KV Power Transmission Network using ANN Based Adaptive STATCOM Device

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***Abstract*— *This paper is targeted on the improvement of the Nigeria 330kV 44Bus network voltage stability using ANN based adaptive STATCOM. The three-phase version of the test network was modelled in MATLAB-SIMULINK for simulations. Using the data obtained from the Transmission Company of Nigeria (TCN), Oshogbo and simulation data; ANN based adaptive STATCOM was developed, trained and deployed to the Test network for compensation of the weak section of the network. Results and analysis of simulations shows that the test network is unstable as the modal analysis revealed the presence of eigenvalue with a negative real part. Yola bus was discovered to be the most vulnerable bus with the highest participating factor and a voltage profile (of 0.83pu) less than acceptable lower limit of 0.95pu. The connection of ANN based adaptive STATCOM improved the stability of the network by enhancing the voltage profile of the network's weakest bus by 22.9%. It was concluded that ANN based adaptive STATCOM was effective in improving the stability of the Nigeria three phase transmission grid network.*

I. INTRODUCTION

The Nigerian 330kV transmission network is characterized by poor generation, poor infrastructure, aged equipment, inadequate transmission capacity and poor maintenance culture. The above inadequacies together with other usual power system contingencies (change in loads, switching actions, loss of generation faults etc) have continued to impact negatively on the stability and security of the power networks. The implications of sustained poor system security and instabilities on the power network is that the power network becomes prone to frequent and long outages, loss of loads, cascaded outages and eventual voltage collapse. Long and frequent outages, or worse still blackouts, have adverse effects on both system equipment and users. Inadequate power supply impacts negatively on socio-economic development of the users. On the other hand, frequent power interruptions can lead to failure of some system equipment, thereby increasing cost of operation of the system (Aneke & et al, (2021), Aneke & Ngang(2021), Ezekiel & Engla (2019))

Power system stability is the capacity of a power system to maintain an operating equilibrium condition after experiencing a physical disturbance (relative to an initial operating condition) such that the system integrity is preserved by keeping most system variables bounded (Kundur, 2004). The above definition suggests that for a power system to remain stable, it should have the ability to adjust and function successfully after undergoing small and severe disturbances such that system variables like voltage magnitude and angle, current, active and reactive power losses.etc remain within the limit of their acceptable values. On the other hand, an unstable system is unable to adjust and function successfully in the event of physical disturbances. Such systems are characterized by a sustained rise in system parameters mentioned above. The consequence of sustained increase in system parameters is cascaded blackouts and eventual system collapse. With the help of stability analysis of power system, it is possible to determine the limits within which the system can operate and the necessary control actions that can be taken to expand the stability boundaries of the network such that normal operating conditions of the system is restored even in the face of high magnitude disturbances(Iyidobi,2018). In power systems, normal operating conditions demand that all buses remain at approximately the same voltage level and within an acceptable range of 0.95pu and 1.05pu. Under normal operation, a system should maintain steady voltage at all buses. Flexible Alternative Current Technology systems (FACTs) devices are power electronics-based power system compensators that are strong, flexible and fast switching. They have been successfully applied in voltage stability enhancement of multi-power system. Static Synchronous Compensator (STATCOM) has been identified as one of the most effective member of the FACTs device family as far as enhancing voltage profile and voltage stability of stressed transmission networks are concerned. STATCOM enhances voltage profile of network buses by providing adequate reactive power support at weak buses. In this thesis, STATCOM shall be used as the compensating device for enhancing voltage stability of the Nigerian 330KV 44bus transmission network. To enhance real time performance of the STATCOM, a properly trained Neural Network model shall be connected to the STATCOM to make its compensation effect adaptive to changes in the network operating conditions.

II. LITERATURE REVIEW

VOLTAGE STABILITY

The power system's ability to sustain continuous voltages at the entire system buses following a subjection to disturbance/contingency from a specified original operating state is referred to as voltage stability. Instability that may arise occurs in the form of a progressive fall or rise of voltages of some buses. Possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators for example, may result from these outages.

Progressive drop in bus voltages can also be linked / associated with rotor going out of step i.e (rotor angle stability). For instance, at midpoints of a power network around to an electrical centre, the synchronism loss of machines which approach 180 degrees causes a sharp drop in voltage at these points. (Smith,J.D,2002).

The function of protective systems is to enable voltages return to convenient levels, and also to split two machine groups; the former however depends on the state of the system after the separation.

The major factor that contributes to the instability of voltage is voltage reduction that occurs due to reactive and active power flowing across an inductive reactance linked to the transmission system. It also limits the power transmissibility possessed by a given transmission network. In the same way, when certain generators reach their armature winding or field time –overlap capacity limit, the power transfer ability in turn, becomes limited. Load is the main driving force for instability of voltage. The power consumed by the load when a perturbation or disturbance occurs is restored through the activities of some components such as the regulators of the distributive voltage, thermostats, motors, and tap-changing transformers.

Voltage minimization is further ascribable to increase in the stress of the high voltage (HV) network stress caused by restored loads. Another scenario that triggers instability of voltage occurs when loading dynamic attempts to reverse the power consumed above the capacity of the connected generation and the transmission network, hence a condition with a prolonged reactive power imbalance results (Smith, J. D (2002); Taylor C.W. (1994); Gao B. *et al.* (1996)).

Voltage stability is a term used to describe the capability of a power system to sustain after a perturbation or during steady state, constant voltages in the power system (Kundur, 1994; Kundur, 2004). This is analogous to the capability of the transmission and generation system to keep up with the dynamics of the load (Cutsem, 1998). Considering the system mechanism, voltage stability can either be a disturbance which is large or small. This means that the voltage stability phenomenon can either be short-lived or long term. The focus of the research work on this paper is long term voltage stability

From Kundur's definition of voltage instability, it can be deduced that lack of voltage stability is voltage instability and it is a consequence of unsteady unacceptable voltages.

The second definition is that "Voltage instability comes to play when there is an attempt by the load dynamics to reverse consumption of power above the required capacity of the combined generation and transmission system." (Cutsem, 1998)

The above definition highlights the major reason for voltage instability; that is, load dynamics which seek to return operation beyond the grid's capacities. However, this definition does not directly proffer measures for the evaluation of the stability of voltage in the system. Nevertheless, this definition is more unambiguous than the first one: in a case where minimized voltages can possibly be caused by instability of the rotor angle, it then follows that there is also a need to establish whether instability of the rotor angle is a causal effect of voltage instability or vice versa.

These two definitions will be used in this paper since they address different aspects and therefore do not contradict each other.

Kundur's definition shall here-in be referred to as the voltage stability definition which is symptom based. In the same way, Van Cutsem's and Vournas' definition is tagged a voltage stability cause-based definition.

Recalling the definition of a power system's stability in the introductory section; Stability of a power system entails the capability of an electrical power system which operates under specified initial conditions to return this system to its equilibrium state after the power system's subjection to physical perturbation. This happens with most variables of the system being bounded so as to maintain the integrity of that power system. In other words, the integrity of such power system is conserved. In practical sense, the system's integrity is said to be conserved when the power system is entirely intact without loads or generators tripping, apart from those that are either tripped intentionally or those ones that are isolated as a result of faulty elements as a means of safeguarding the operation of the remaining sections of the system.

The power system is to a great degree, a non-linear system whose operational environment, generator outputs, loads, and major functional parameters change constantly. More so, in the presence of a disturbance, the system's stability is dependent on some factors, such as: initial operating conditions, and nature of the system's motion around an equilibrium position. The different operating forces which exist in this system are instantaneously equal to one complete cycle or above a cycle in the equilibrium set.

The power system is usually bombarded with various amounts of disturbances, ranging from small to large. Load variation disturbances are considered as small disturbances, although the system has to be made in such fashion that it can easily adjust to these varying conditions so as to function properly. In addition to that, it is imperative that the system must be designed to be able to overcome large disturbances with more serious consequences, some of which include large generation loss and short circuiting of a transmission line. One of the features of large disturbance is that as a result of faulty components being isolated, structural changes may occur.

The nature of a physical disturbance of a power system at equilibrium set determines whether or not the system may be stable or unstable. It then goes without saying that it is impossible and a waste of resources to model a power system that will be stable for all contingencies. Usually, the contingency design is chosen based on how high the probability of its occurrence is. Evaluation of the stability of large disturbance involves nonlinear effects that render the linearization of equation inapplicable.

The power system's response to perturbation may be attributed to the equipment in use. For example, the isolation of a critical component by a protective relay due to its faultiness will result to a power flow variation, change in the machine's rotor speeds and variation in the network bus voltages; the voltage regulators of the transmission system and the generator will both be actuated by voltage variation; also, speed variations of generators will activate prime mover governors. Variations of frequency as well as voltage affect the loads of the system also to different degrees which is a function of their features. Other protective devices may react to changes in variables of the system and may thereby cause the equipment of the circuit breaker to skip, which in turn weakens the given system and consequently can result to instability of the system.

However, it is observed that systems frequently experience little magnitude of power/voltage fluctuations of small magnitude. Therefore, to assess the stability of a system when a specific disturbance is induced, it is right to assume that the actual operating condition of the steady-state is in its original state.

Static Synchronous Compensator (STATCOM)

This device is the shunt element in the UPFC. It has found wide application in FACTS, and its main purpose is to support the working potential difference of the bus to which it is electrically installed and maintain stability of the dc-link capacitor voltage.

This device is designed with a matching transformer with parallel connection orientation to the transmission line, an inherent commutated switching power converter and a DC link as shown below.

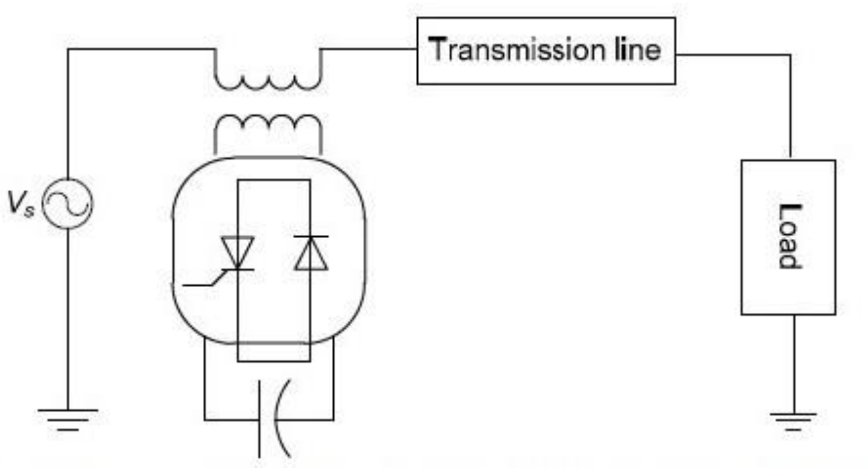

Fig.1: A STATCOM controlled two-bus network; Source: (Shakarami and Kazemi, 2010)

A DC input supplied to the circuit is converted to AC at the output. This controls the real power and as well the reactive power developed in the network. It also provides reactive power and controls active power flow, thereby enhancing the PTC of congested grid(Shakarami and Kazemi, 2010). In steady state analysis, the substitution of active power between the STATCOM and the transmission system can be neglected. Hence reactive only circulates between them (Zhang *et al.*, 2004).

STATCOMs generally, do not need many reactive components in order to inject reactive power (either capacitive or inductive) to high voltage transmission network, unlike SVCs. One colossal advantage of this device is that it requires smaller area and higher reactive power output at a low voltage transmission line since it acts an independent current source. More so, considering the dynamic stability, STATCOM affords a better suppressing behaviour than SVC since it can exchange active power with system transiently.

Artificial Neural Network

Artificial neural network (ANN) is a generic nomenclature for a set of computing systems that closely operates like a human brain. When the interconnected units or nodes (artificial neurons) of the ANN are determined, each input signal is weighted, summed together, and transferred to an activation function which is used to represent the neurons in the biological brain. At the nodes, signal strength is either increased or decreased. Usually, neurons are divided into different layers, and these layers may transform differently on their inputs as shown in figure 2.

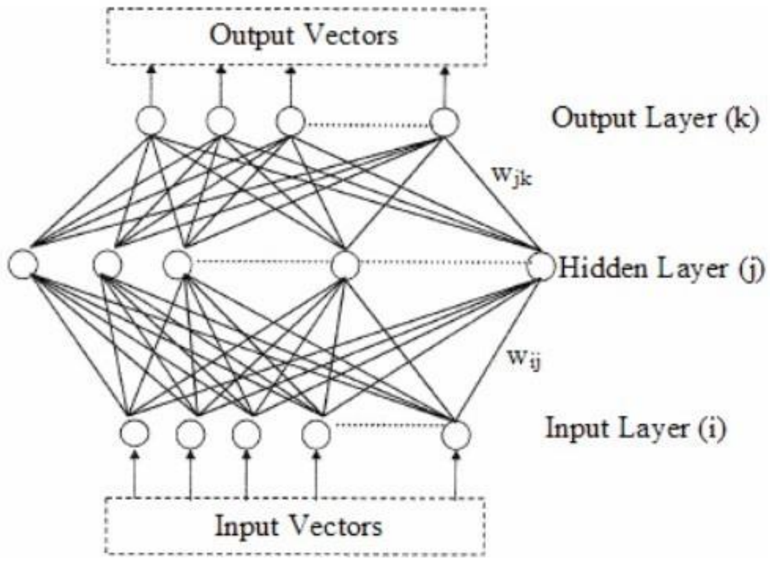

Fig.2: Typical ANN architecture model; Source: (Abu-Siada etal,2010)

Each connected neurons transmit a signal like synapses to other neurons when the output signal exceeds the threshold limit of the neuron; and by considering several examples, the connected systems learn to perform tasks without being explicitly programmed to follow certain protocols or specific task routines. This unusual trend can be seen in the technology which recognizes image; where the ANN trains itself to recognize images explicitly labeled "human face". However, the system can use the results obtained to identify the human face in other images. They do these without prior knowledge of human beings. This occurs because the system has automatically generated identifying features from the examples that they have learned.

O. Borazjani, M. Roosta, K. Isapour, and A. R. Rajabi (2015) proposed a fast technique to monitor and improve power system stability. They used an ANN-based method. In their work, they trained three layers feed-forward ANN along with back-propagation to give an optimum rescheduling of reactive power control variables needed to maintain voltage stability in the continuous utilization of the power system network; and, excitation generators, switchable VAR compensators, and OLTC transformers are used as reactive power control variables.

They make use of LP technique to determine the training data by solving various system conditions and implemented this method on a modified IEEE 30-bus test system. The results obtained indicate that at a high level of precision and speed, the ANN approach can enhance voltage stability in the power systems from a minimum range to a maximum range of load changes. A. Abu-Siada, S. Islam, and E.A. Mohamed (2010) proposed an improved technique for the on-line prediction of OLTC transformer configuration, and they also analyzed the maximum power to the load center. In their work, IEEE Six-bus power system was employed to evaluate the method, and the numerical results obtained indicate that the function of the OLTC transformer imposes a colossal effect on the highest limit of the power transfer as well as the stability margin.

III. METHODOLOGY

STATCOM SIMULINK MODEL

The basic building block of the STATCOM is a Voltage Source Converter (VSC) and the device is shunt connected to the test network through a coupling inductance. The coupling inductance can be a transformer or a reactor if the device is designed for direct connection to the bus bars voltage level. In this paper, the coupling inductance is a transformer. The STATCOM was modeled as an AC-voltage source to enable the magnitude, the phase angle and the frequency of the output voltage to be controllable.

To achieve this objective, a new model work space is created in Power System tool box (PSAT) Simulink environment. From PSAT library, the required component blocks (including transformer, voltage source converter, capacitor etc) are imported into the newly created work space. Each of the blocks is configured to reflect their ratings. At the end of the configuration, they are then linked together to form the STATCOM model.

Simulation is performed on the developed model to ensure that the model will perform as expected when connected to the test network. Simulating the STATCOM model is essentially to correct the error (s) that might pop up during the main simulation. Finally the model is saved to file for later use. The developed STATCOM MODEL is as shown below in figure 3 below.

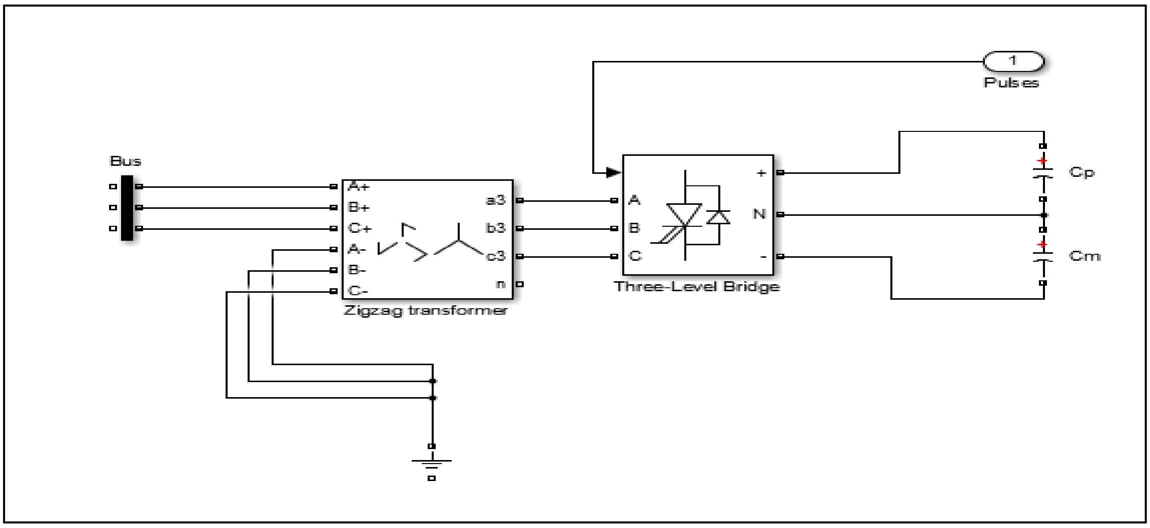

Fig.3: STATCOM simulink model

STATCOM CONTROL STRATEGY

The STATCOM is modeled as a voltage source inverter (VSI). Here the VSI converts direct current input voltage from the capacitor to AC output voltage supplied to the network bus. The output voltage supplied to the network bus helps to compensate active and reactive power demand at the bus where STATCOM is connected. Fig.4 shows the basic structure of ANN controlled STATCOM. The bus voltage and angle can be adjusted by controlling the injected real and reactive power at the AC network bus.

The expression for this injected real and reactive power at AC network bus as deduced by Ahmadi and Alinezhad (2009) is adapted for this modeling and is given below:

$$V_{dc} = \frac{-R(Q^2+P^2)}{CV^2 x\, V_{dc}} - \frac{V_{dc}}{CV_{dc}} + \frac{P}{CV_{dc}} \qquad (1)$$

The injected power at the AC network bus can be represented as:

$$P = V^2G - KV_{dc}\, VG \cos(\theta-\alpha) - KV_{dc}\, VB\sin(\theta-\alpha) \qquad (2)$$

$$Q = V^2B - KV_{dc}\, VB\cos(\theta-\alpha) - KV_{dc}\, VG\sin(\theta-\alpha) \qquad (3)$$

Where $K = \sqrt{\frac{3}{8m}}$

P= AC bus real power

Q= AC bus reactive power

V= Magnitude bus voltage

V_{dc} =Capacitor voltage

G= Conductance of the system

θ= Voltage angle

α= Firing angle of GTO

B= Subsceptance of the system

K= Constant

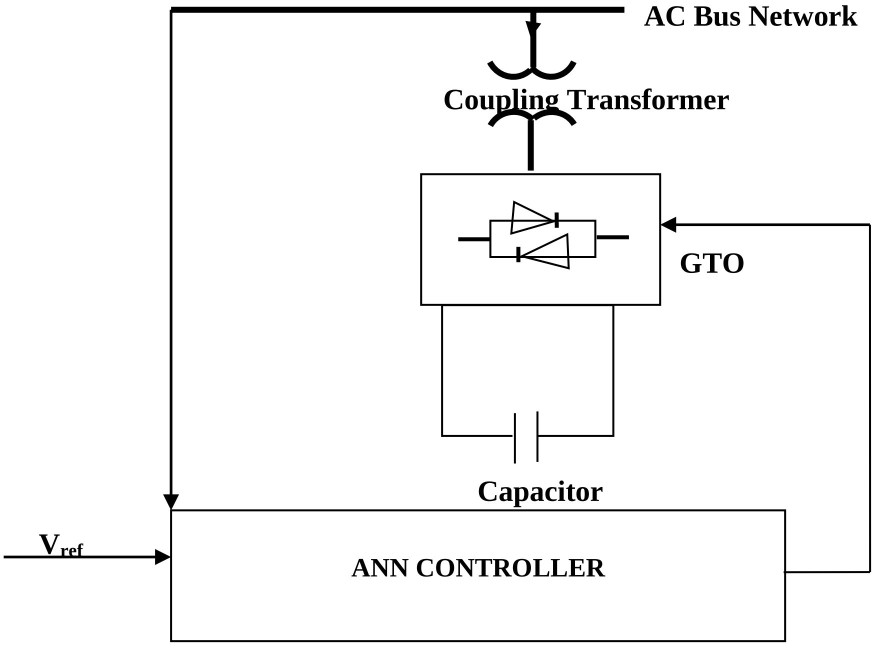

Fig. 4: Structure of ANN Controlled STATCOM

From equations 1 and 2 it can be seen that the injected real power (P) and the reactive power (Q) at the AC network bus are functions of the firing angle ‘α’’. This implies that to adjust the injected active and reactive power (P&Q) and hence the AC voltage; the firing angle of the thyristor in the STATCOM need to be adjusted. The control strategy is therefore to use a trained ANN controller that can sense the AC voltage and compare it with the reference voltage and then adjust the voltage closer to the reference value. By doing this, the voltage stability of the network is enhanced and voltage collapse in the network mitigated.

DEVELOPMENT OF ARTIFICIAL NEURAL NETWORK (ANN) ADAPTIVE CONTROLLER FOR THE STATCOM

By varying the value of the firing angles/pulses of the STATCOM bridges, STATCOM can enhance or reduce voltage profile of buses depending on the nature of compensation needed at the buses. In event of low voltage profiles at buses, STATCOM is able to enhance the voltage level but during over voltages, STATCOM is also able to reduce voltage level at the affected buses. The adaptive capacity, intelligence or control action required by STATCOM to adjust the firing angles/pulses of its bridges so as to respond adequately to the challenges of the network is provided in this work by an ANN adaptive controller. To effectively make the STATCOM compensation adaptive to the changes in the network, the ANN adaptive controller is rigorously trained with bus voltages from load flow and compensating firing angles/pulses from STATCOM.

To obtain the training data for the neural network, the three phase test network will be simulated under different working conditions to obtain optimum voltage profile values as well as ones below the minimum accepted value of 0.95 at the weakest bus with no STATCOM connected. STATCOM was then connected to the three phase test network. The firing pulses/angles of the STATCOM is then adjusted so as to keep the voltage profile of the weakest bus within acceptable range of 0.95pu to 1.0pu. The voltage values obtained in the first simulation (without STATCOM) and their corresponding firing angles/pulses in the second simulation (with STATCOM) form the input and target training data respectively.

To develop the neural network for making the STATCOM adaptive, the ANN fitting application environment is opened in Matlab. From the ANN fitting application environment, the ANN is created with three inputs (V_a, V_b, V_c) and 48 outputs representing the firing pulses. After creating the network, the input and target data already preloaded in the Matlab workspace is used to train the network. The training of the adaptive ANN was done offline.

After a successful training using Levemberg-Marquardt algorithm, the trained network is then deployed into a Simulink model and its code generated. The developed simulink model and its network architecture are as shown in figure 5 and 6 respectively below. It is this Simulink model of the trained ANN that is connected to the STATCOM to make it adaptive.

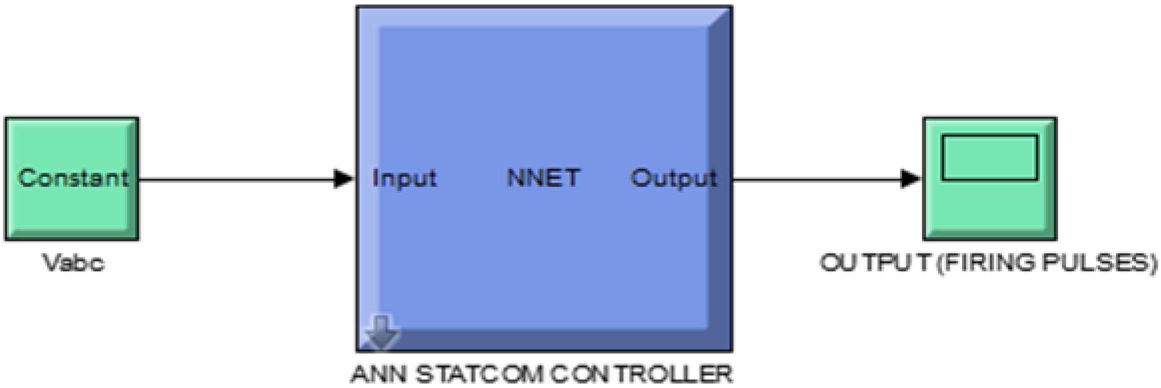

Fig.5: Simulink model of ANN BASED ADAPTIVE STATCOM

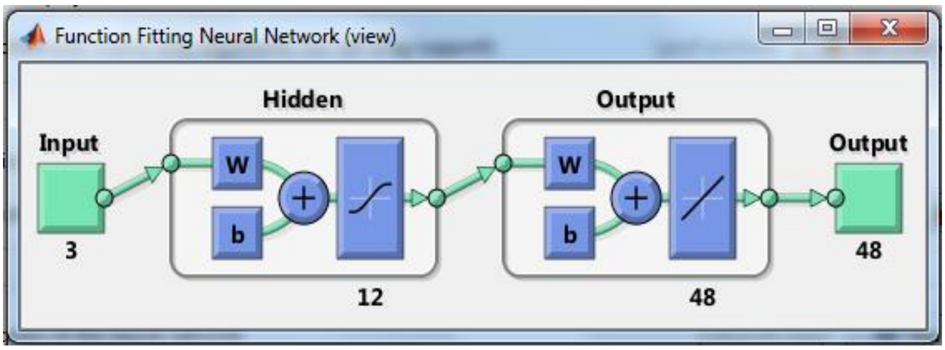

Fig.6: Architecture of the ANN BASED ADAPTIVE STATCOM

There is need to develop the three phase version of the PSAT simulink model of the test network as it will be cumbersome to handle this large number of buses in three phase network without this reduced version. This became necessary because of the need to perform real-time simulation on the test network which the PSAT simulink model can't perform.

To overcome this uphill task, the test network was divided into three sections: one section is the section which contains the weakest bus (Yola) and the other two sections were modeled into two equivalent networks as shown below in figure 7.

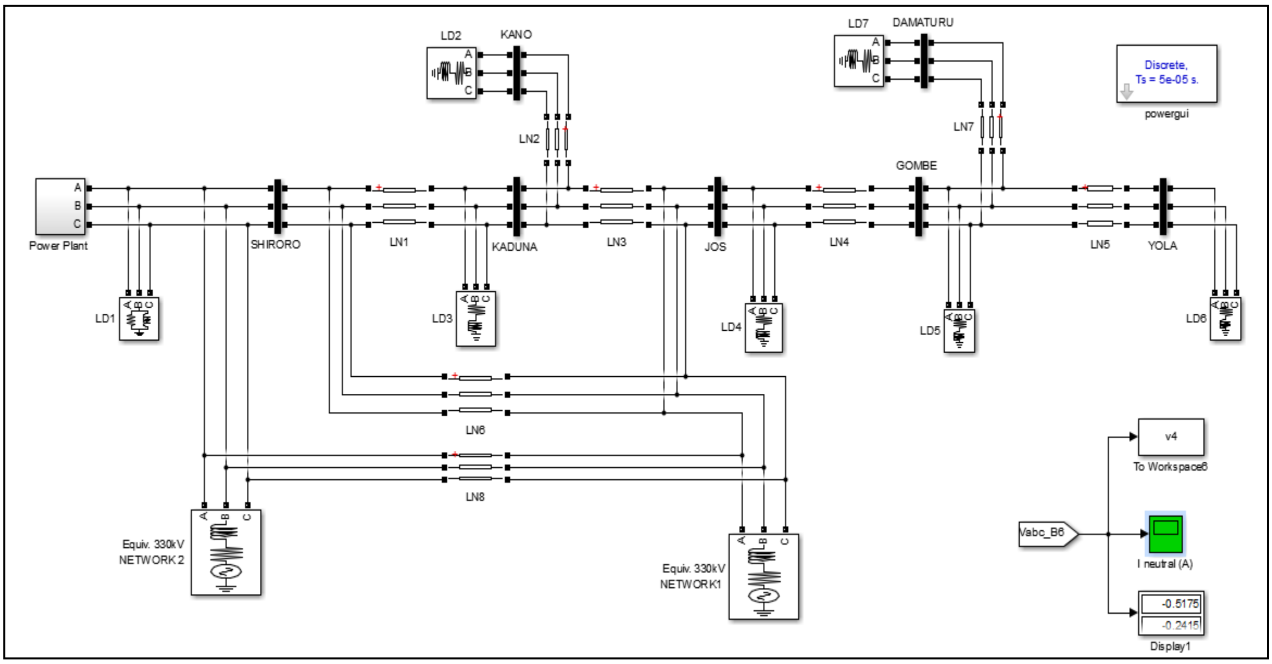

Fig.7: Reduced Version of the three Phase Simulink Model of the Nigerian 330kV Transmission Network.

IV. RESULTS AND DISCUSSIONS

Determination of the Stability of the Test Network Using Modal Analysis

From the plot of the system's eigenvalue in figure 8, it can be seen clearly that without STATCOM the system had an eigenvalue with a negative real path for the base case. This implies that at normal condition, the system is unstable. There is therefore need to connect a compensating device so as to enhance the stability of the network and thereby preventing the network from moving to collapse point. This is achieved by moving any negative real part of the eigenvalue to the positive part.

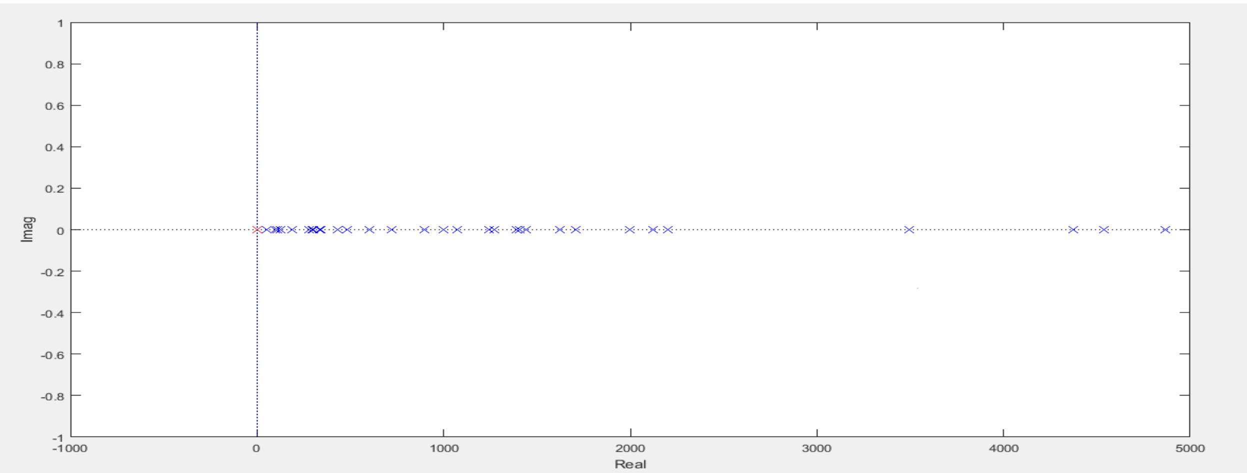

Fig.8: Plot of real and imaginary part the system eigenvalue for normal working condition.

Determination of the weakest bus (es) of the test network using the participating factors

Appendix 2 shows the respective participating factors for the identified critical modes of the base case presented in appendix 1. From appendix 2, it can be seen that for the highest participating factor values was 0.309011 corresponding to Yola bus. Since Yola has the highest participating factor, Yola bus is adjudged the weakest bus. This implies that the activities at Yola Bus contribute most to the networks instability. The above result indicates that compensation on the network shall be implemented on the Yola bus. The adaptive STATCOM will therefore be installed at Yola bus for effective compensation in the entire network.

Evaluation of the performance of the adaptive STATCOM

The performance of the adaptive STATCOM compensator and its controller shall be done by comparing the voltage profile of the weakest bus (Yola) without compensation with the voltage profile with adaptive compensation. In the earlier section, Yola bus was spotted as the weakest bus. Voltage stability of the network will be restored if compensation on Yola bus brings its voltage profile to a value within the acceptable stability limit of 0.95pu to 1.05pu. The three phase network of the test system is simulated without any form of compensation. The result obtained after this simulation is shown in figure 9. The adaptive STATCOM is then connected to the three phase test network and simulation carried out. The result of this simulation is shown in figure 11. The network connection corresponding to result of figure 11 (test network with STATCOM) is shown in figure 10.

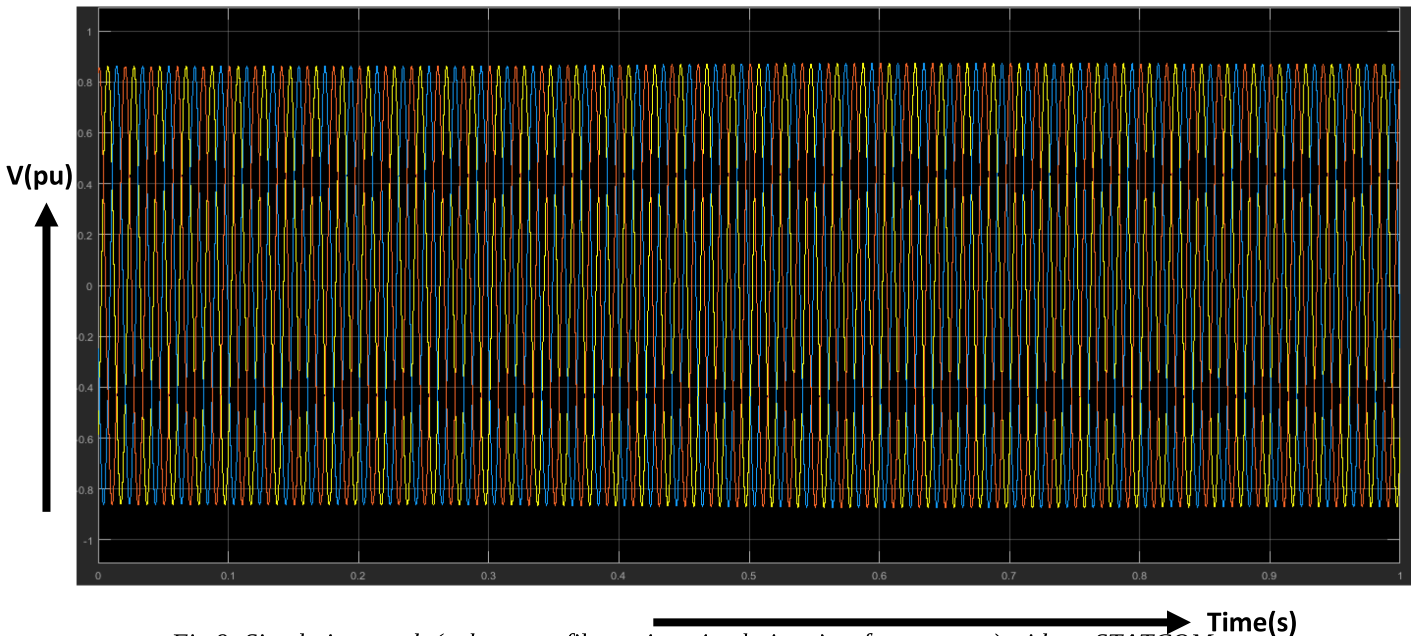

Fig.9: Simulation result (voltage profile against simulation time for case one) with no STATCOM

From figure 9, it can be seen that the voltage profile of the weakest bus (Yola) is 0.83pu. This value is clearly below the minimum acceptable value of 0.95pu. There is therefore need for compensation at the weakest bus to bring the system back to stability. STATCOM controlled by ANN was connected across the Yola bus and the closest generator at Shiroro bus as shown in figure 10. The result of simulation carried out on figure 10 connection is shown in figure 11.

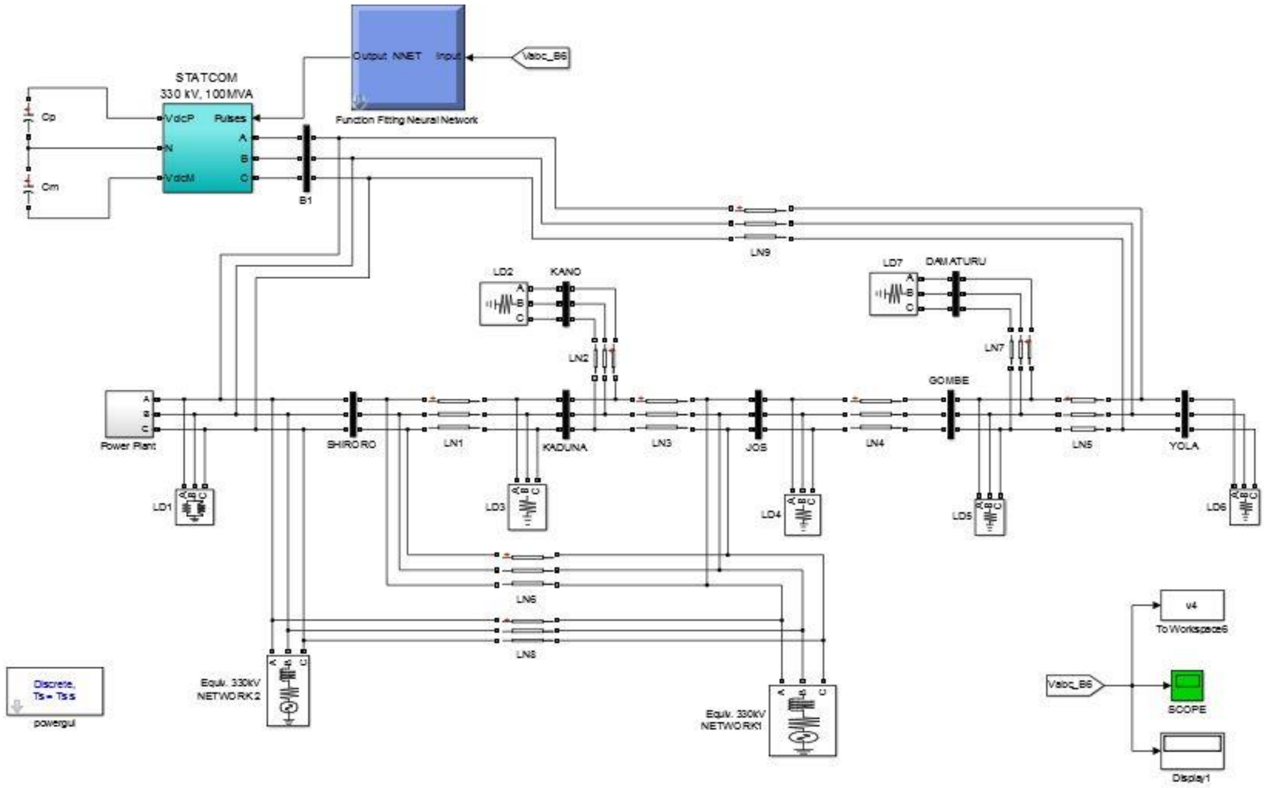

Fig.10: Three Phase Simulink Model of the Nigerian 330kV Transmission Network with ANN Based Adaptive STATCOM connected.

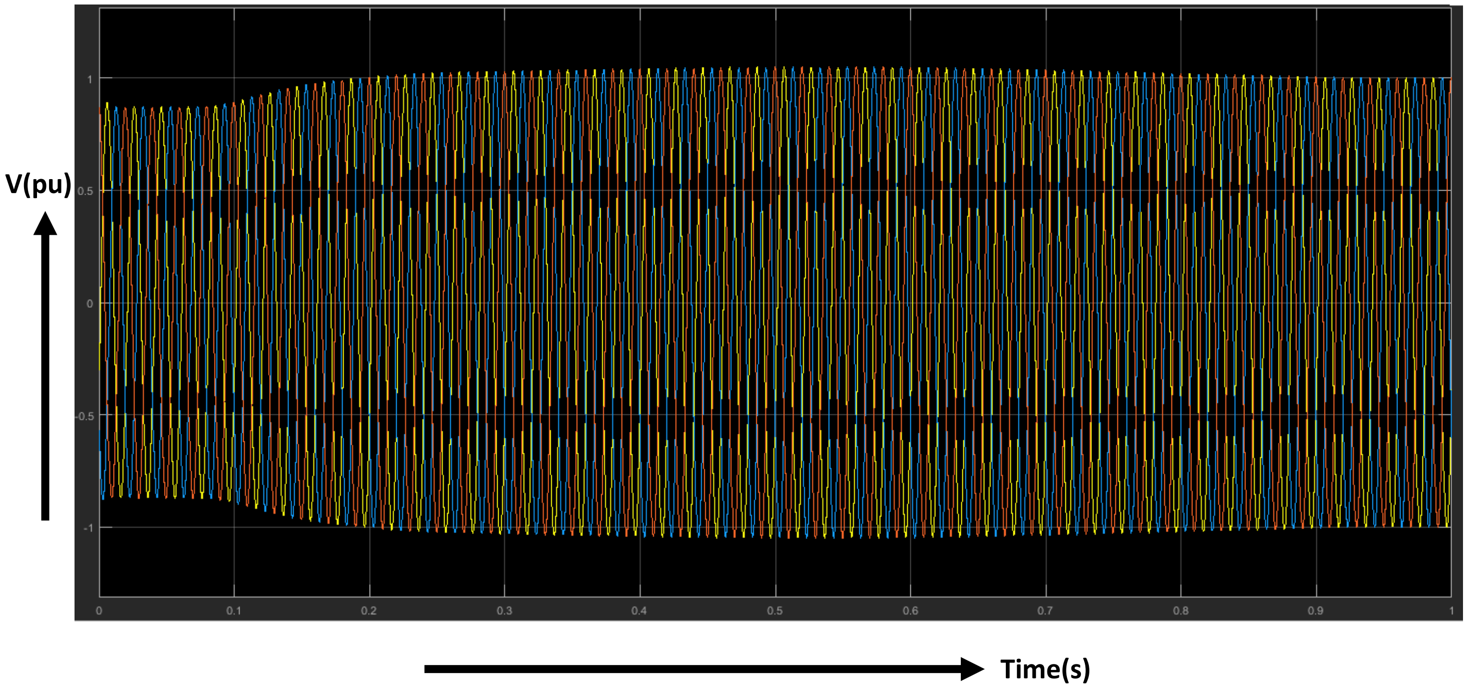

Fig.11: Simulation result (voltage profile against simulation time for case one) with Adaptive STATCOM connected.

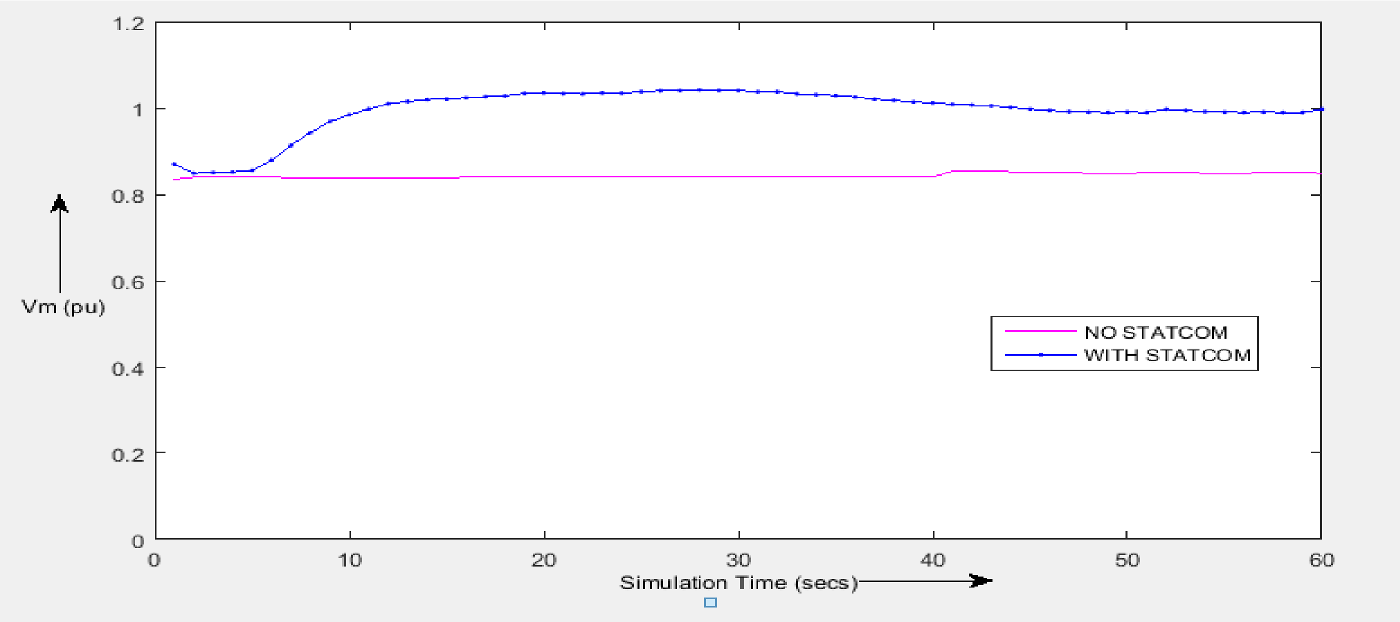

Fig.12: Simulation result (voltage profile against simulation time for case one) both when Adaptive STATCOM is connected and when not connected.

From figure 11, it can be seen that after 0.2 seconds, the voltage profile of bus Yola stabilized at 1.02pu. This value is within the acceptable range of 0.95 to 1.05pu voltage profile. This shows that for case one (no contingency), the ANN based adaptive STATCOM was able to bring the system to stability when connected.

As can be seen from figure 12, the peak voltage level without the adaptive STATCOM remained at approximately 0.83pu all through the simulation but when the adaptive STATCOM was incorporated, the peak voltage started rising and finally settled round 1.02pu. The incorporation of the ANN based adaptive STATCOM was able to increase the voltage profile of the weakest bus from0.83pu to 1.02pu. This increase represents a 22.9% improvement.

V. CONCLUSION

The test network was found to be unstable as the modal analysis revealed the presence of eigenvalue with a negative real part.Yola bus was discovered to be the most vulnerable bus with the highest participating factor and a voltage profile (of 0.83pu) less than acceptable lower limit of 0.95pu. ANN based adaptive STATCOM improved the stability of the network by enhancing the voltage profile of the network weakest bus by 22.9%.

It can be concluded that ANN based adaptive STATCOM was effective in improving the stability of the Nigerian three phase transmission grid network.

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