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ANN Based Voltage Stability Enhancement and Voltage Collapse Reduction in Stressed Multi-Bus Network using Controlled STATCOM

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Abstract: This study aims to increase voltage stability and reduce voltage collapse in the 44-bus 330KV grid transmission network in Nigeria. The reduced Jacobian matrix, JR, has been decreased, and the modal approach uses steady state mode to determine the smallest eigenvalue and all related eigenvectors. In PSAT-MATLAB, the network model was created, and load flow was implemented on the network. Results and analysis indicated that the 44-bus grid network in Nigeria was unstable because eigenvalues with a negative real portion were detected in the modal analysis of the data. The vulnerable buses were also found to be the Gombe, Damaturu, and Yola buses since their voltage profiles were below the 0.95pu IEEE standard voltage limit. Based on a review of the contributing factors, the Yola bus was identified as the least reliable bus. In order to provide compensation prior to the implementation of the contingency, ANN controlled STATCOM was attached at this bus. According to the results, when the network was stressed by doubling the loads on each bus, the connection of an ANN controlled STATCOM increased the network's voltage stability by 56.9% and prolonged the point of voltage collapse by 122% in comparison to the point of voltage collapse when STATCOM was not connected. The voltage stability of the 44-bus 330KV transmission power network in Nigeria was enhanced, and voltage collapse was minimised in the network during a contingency of significant rise in load on the network, according to the results of the study.

Key Words: PV Curve, Modal, Eigenvalue, Voltage Stability, Participating Factors, STATCOM.

INTRODUCTION

Every multi-bus electrical network behaves dynamically. Therefore, it could be misleading to assess the stability of a multi-bus power network only under typical operating circumstances. During operation, it is normal to expect that power networks may face some level of stress. This stress may be brought on by load changes, switching actions, or even malfunctioning situations. In order to improve the network's voltage stability and reduce voltage collapse in the network using an artificial neural network controlled STATCOM device, this paper will evaluate the voltage stability and point of voltage collapse of a multi-bus power grid transmission network during a sudden increase in load. The Nigerian 44-bus 330KV transmission grid network will be the subject of this grid power network study. Inadequacies in the Nigerian grid transmission network have long been known to exist. These deficiencies include outdated equipment, poor maintenance practises, inadequate generating, and inadequate transmission capabilities. Due to this circumstance, the grid networks are vulnerable to instability, frequent voltage collapses, and blackouts. Stability of voltage in a power system refers to a network's ability to maintain consistent, satisfactory voltage levels at all buses in a system under normal initial operating conditions and after disturbances (Kundur, 1994). The ability to deliver reactive and actual power from the generation sources to the load centres throughout the steady working states is the important characteristic of voltage stability. Voltage stability is the ability to keep the desired voltage level reaching the loads at all times (Aneke etal, 2021). On a complex network, persistent voltage instabilities have the immediate effects of voltage breakdown and cascading blackouts. Therefore, a good voltage stability evaluation that should be followed by efficient reactive power compensation is required to successfully prevent voltage collapse in our networks. When it comes to improving the voltage profile and voltage stability of stressed transmission networks, STATCOM has been found to be one of the most effective members of the flexible alternating current transmission system (FACTS) device family. By providing sufficient reactive power compensation at the vulnerable buses, STATCOM improves the voltage profile of the network buses. In this thesis, the Nigerian 330KV, 44-buse transmission network's voltage stability will be improved by using STATCOM as a compensating device. A trained and deployed neural network controller must be used to regulate the STATCOM in order to make its response adaptive to network changes. This study aims to increase voltage stability and reduce voltage collapse in the 44-bus 330KV grid transmission network in Nigeria.

A) Voltage Stability and Voltage Collapse:

Voltage stability refers to a power system's capacity to maintain constant voltages across all system buses after being subjected to disturbances or changes from a predetermined initial operating condition. Therefore, a factor that affects the stability of voltage is a system's ability to maintain or restore balance between the load supply and load demand. Instability may develop if the voltages on some of the buses gradually rise or decline. A load loss in a specific location or a break in the transmission lines and other components by the systems that insulate them, leading to an increase in outages, are signs of voltage instability. The failure of some generators to maintain synchronism is a good illustration of this occurrence of outages. Bus voltages gradually lowering may also be related to the rotor moving out of phase, i.e. (rotor angle stability). For instance, a sharp drop in voltage occurs at the midpoints of a power network as it circles an electrical centre due to the synchronism loss of machines that approach 180 degrees. J.D. Smith (2002). Both splitting two machine groups and allowing voltages to fall to comfortable levels are functions of protective systems; the former, however, depends on the system's condition prior to the separation. Voltage decrease brought on by reactive and active power flowing across an inductive reactance connected to the transmission system is the main cause of voltage instability. Additionally, it restricts a transmission network's ability to transmit large amounts of power. The ability to transfer power also decreases when some generators reach their armature winding or field time-overlap capacity limits. The primary cause of voltage instability is load. When a perturbation or disturbance occurs, various components, including the regulators of the distributive voltage, thermostats, motors, and tap-changing transformers, go to work to restore the power absorbed by the load. Further explanation for voltage minimization is the rise in high voltage (HV) network stress brought on by restored loads. According to Smith, J. D. (2002), Taylor, C. W. (1994), Gao, et al. (1996), another situation that causes voltage instability occurs when the loading dynamic tries to reverse the power consumed over the capacity of the connected generation and the transmission network. The ability of a power system to maintain steady, consistent voltages during steady state conditions or after a disturbance is referred to as voltage stability (Kundur, 1994; Kundur, 2004). This is comparable to the transmission and generation system's capacity to keep up with the load's dynamics (Cutsem, 1998). Voltage stability can be a significant or little disturbance depending on the system's process. As a result, the voltage stability phenomena may be either transient or persistent. The long-term voltage stability is the main research topic for this thesis. According to Kundur's definition of voltage instability, a lack of voltage stability is a form of voltage instability that results from unstable, undesirable voltages. The capacity of an electrical power system operating under specific beginning circumstances to revert to its equilibrium state after being subjected to physical disruption is a requirement for a power system to be considered stable. To preserve the integrity of that power system, this occurs with the majority of the system's variables bound. In other words, such a power system maintains its integrity. Practically speaking, the power system is said to be completely intact when no loads or generators trip, with the exception of those that are either purposely tripped or those that are isolated due to malfunctioning components in order to protect the operation of the other parts of the system. The operational environment, generator outputs, loads, and the main functional characteristics of the power system are, to a large extent, non-linear systems. More specifically, the stability of the system in the face of a disturbance depends on a number of variables, including the system's initial operating circumstances and the way it moves around an equilibrium point. In this system, the various operating forces are immediately equal to or greater than one cycle of the equilibrium set. The electricity system is frequently subjected to disturbances of all sizes, from tiny to big. Although load variation disturbances are regarded as minor disturbances, the system must be built in such a way that it can quickly adapt to these changing conditions in order to work well. Additionally, it is essential that the system be built with the ability to overcome. large disturbances with more serious consequences, some of which include large generation loss and short circuiting of a transmission line. Voltage collapse, according to Kundur (1994) “is the process by which the system of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system” (Kundur, 1994)

Whether any of the loads are intentionally or unintentionally tripped, reliable operation can continue at low voltage even after the transformer tap changers reach the top of their boost range. Voltage reduction, which happens as a result of reactive and active power flowing across inductive reactance connected to a transmission system, has already been mentioned as the main factor that contributes to the instability of voltage. This limits the transmission network's ability to support voltage and convey power. When some generators approach the range of their armature or maximum current duration over-load capability, voltage support and power transfer are further restricted. Any time a system disruption causes a rise in reactive power demand that is more than the maximum sustainability of the reactive power resources available, the stability of voltage is deemed fragile. Basic phenomena associated with voltage stability/instability include temporary load reduction, large (reactive) loading in a particular area reducing voltage, reduced area transfer capacity, recovery of load demand, further voltage reduction, and voltage collapse in the event that load flow cannot be resolved.

B) Basic Principle of Operation of STATCOM

Figure1 presents the schematic diagram of a STATCOM based on a voltage sourced. A STATCOM device is basically modeled as a controlled reactive power source. It provides the desired reactive power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage source converter (VSC). In Figure1, a STATCOM is seen as an adjustable voltage source behind a reactance, meaning that capacitor banks and shunt reactors are not needed for reactive power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact.

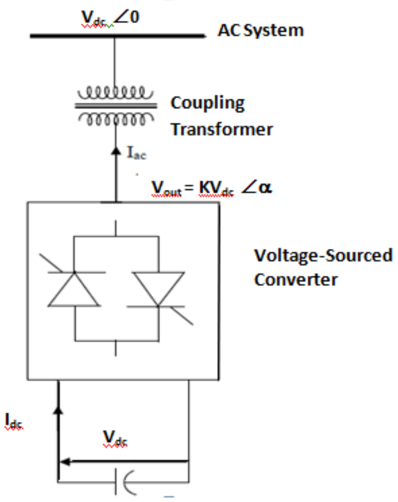

Figure 1: STATCOM Schematic Diagram

MATERIALS AND METHOD

The approach used in this research paper is to first evaluate the voltage stability of the 44-bus 330KV Nigeria network (test network). From the result, it can be established whether the network require any compensation or not. The stability evaluation will also reveal the weakest bus at which any compensation will be implemented for efficiency. The modal analysis technique was used to evaluate the network stability. Computing the participating factor also revealed the most vulnerable bus. A three phase STATCOM was developed in Simulink/Matlab. An ANN controller was also created, trained and deployed into a Simulink model to control the STATCOM. A reduced three phase version of the Nigeria 44-bus 330KV transmission network was also developed in Simulink/Matlab. The performance of the entire system was then evaluated when the network was stressed by increasing its loading suddenly.

A) Voltage Stability Evaluation of the Test Network

After performing load flow on the network in order to evaluate if the network is stable or not and to identify the network's weakest bus, modal analysis is used to determine the voltage stability of the test network. In essence, modal analysis determines the network's eigenvalues and the contributing elements to those values. The eigenvalues of a reduced system steady-state Jacobian matrix (J R) that maintains the Q-V relationship in the network must be calculated for the modal analysis. It should be noted that (J R) does not reflect a dynamic system; rather, it shows the linearized relationship between the incremental changes in bus voltage magnitude and bus reactive power injection. The system is voltage-stable if the eigenvalue is positive, which shows that the modal voltage and modal reactive power are oriented in the same direction. A negative eigenvalue, on the other hand, means that the system is voltage-unstable since the modal voltage and modal reactive power are moving in the opposite directions. The most important nodes that can cause the system to become unstable are highlighted by participation factors. In general, the solution that can be applied on a bus to stabilise the node is easier to implement the bigger the size of the participation factor of a bus in a certain mode. Power System Analysis Toolbox (PSAT), a Matlab programme, was used to implement load flow and modal analysis on the test network. Figures 5 and 6 exhibit the results of the load flow and modal analyses, respectively.

B) STATCOM Design

The specifications of the primary STATCOM device components must be established for this design. The coupling transformer, the thyristor bridges (voltage source converter), and the direct current (dc) capacitor are the three main parts of the STATCOM, as can be seen from the schematic diagram in figure 1. It is clear from the aforementioned components that the dc capacitor is the active component that necessitates mathematical design. This is due to the fact that a suitable design must guarantee that the capacitor's size can support the power that it must store and discharge in order to compensate for reactive power. Once the dc capacitor's capacitance has been established, the coupling transformer and thyristor bridge ratings must be checked to make sure they can resist the capacitor's charging current and voltage. Hannan (2012) design expressions were employed for this design and are stated as follows to calculate the value of the dc capacitor for the STATCOM: Power that is sent to the AC network for reactive power compensation is lost by the capacitor in the STATCOM. The energy shift that the charged capacitor loses in one cycle of a sign wave in AC form to the network is given as

$$\Delta E_c(t) = \frac{C_{dc}}{2}(V_{cmax}^2 - V_{dc}^2) = \text{Power dissipated over one period} \qquad (1)$$

Where ΔE_c (t) = Energy loss of capacitor in one period or on cycle. Note that this is equivalent to power dissipated by the capacitor in one period ie energy/Time. Where time = 1

V_{cmax} = Set upper limit of the voltage across capacitor when fully charged.

V_{dc} = capacitor voltage after supplying for a time of one period.

Note that power dissipated by a capacitor is given as $\frac{1}{2}CV^2$ which is equivalent to $\frac{C_{dc}}{2}(V_{cmax}^2 - V_{dc}^2)$

Now, this power dissipated is also equal to the power used in charging the capacitors for the same 1 period.

This implies that;

$$\Delta E_c(t) = \int_o^T V_s \sin wt \, I_{Sc} \sin wt dt \qquad (2)$$

$$ie\ P_c = VIdt$$

Simplifying (2) becomes

$$\Delta E_c(t) = V_{SC} I_{SC} \int_0^T \sin^2 wt dt = \frac{1}{2} V_{SC} I_{SC} T$$

where V_{SC} =Charging Voltage, I_{SC} =charging current and T=Period

$$\therefore \Delta E_c(t) = \frac{V_{SC} I_{SC} T}{2} \qquad (3)$$

Equating (3) to (1) gives

$$\frac{C_{dc}}{2}(V_{cmax}^2 - V_{dc}^2) = \frac{1}{2} V_{SC} I_{SC} T \qquad (4)$$

While the load current is reduced, the charging current I_{SC} will be equal to the change in load current ΔI_L. Hence, an extra utility source current ΔI_L will charge the energy storage capacitor. Substituting ΔI_L for I_{SC}, equation (4) becomes

$$C_{dc} = \frac{V_{SC}\,\Delta IL x T}{V_{cmax}^2 - V_{dc}^2}\ for\ single\ phase$$

and

$$C_{dc} = \frac{3\,\Delta IL V_{SC} x T}{V_{cmax}^2 - V_d^2} \text{ for three phase network} \qquad (5)$$

C) STATCOM Simulink Model

A Voltage Source Converter (VSC) is the fundamental component of the STATCOM and is shunt connected to the test network via a coupling inductance. If the device is intended for direct connection to the voltage level of the bus bars, the coupling inductance may be either a reactor or a transformer. The coupling inductance in this work is a transformer. To enable control of the output voltage's magnitude, phase angle, and frequency, the STATCOM was represented as an AC voltage source. In the Power System Tool Box (PSAT) Simulink environment, a new model work space is built in order to accomplish this goal. The necessary component blocks (such as a transformer, voltage source converter, capacitor, etc.) are imported into the freshly constructed work space from the PSAT library. Each block has been set up to reflect the ratings. They are then connected to one another to create the STATCOM model at the conclusion of the configuration. The built model is simulated to make sure it will function as expected when linked to the test network. The main purpose of simulating the STATCOM model is to fix any errors that may have occurred during the primary simulation. The model is then saved to a file for future use. The created STATCOM MODEL is depicted in figure 2 below.

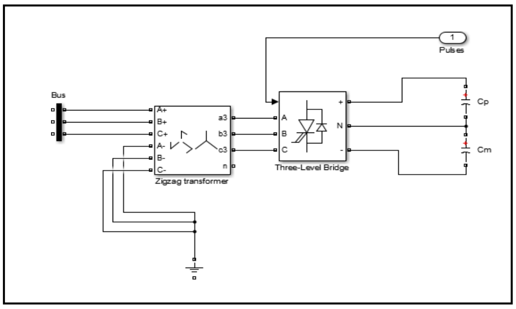

Figure 2: STATCOM Simulink model

D) STATCOM Control Strategy

A voltage source inverter is how the STATCOM is modelled (VSI). Here, the VSI transforms the capacitor's direct current input voltage into AC output voltage that is sent to the network bus. In order to balance out the active and reactive power demands at the bus where STATCOM is linked, the output voltage delivered to the network bus. The fundamental layout of an ANN operated STATCOM is depicted in Figure 3. By adjusting the injected actual and reactive power at the AC network bus, the bus voltage and angle can be changed.

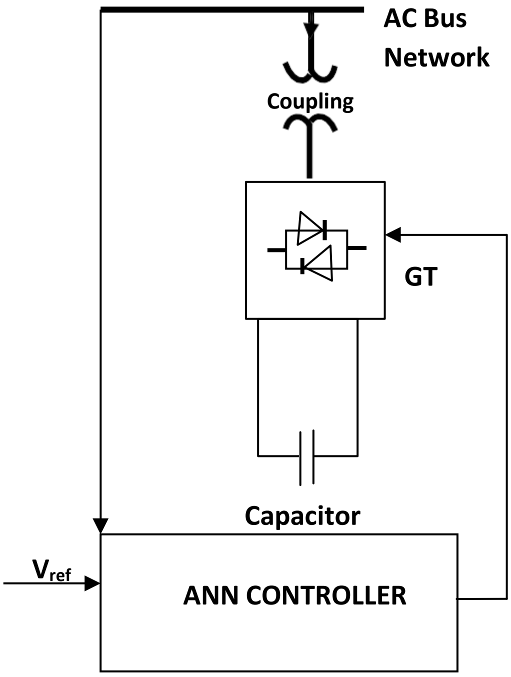

Figure 3: Structure of ANN Controlled STATCOM

Here, a trained ANN controller is used as part of the control strategy to measure the AC voltage, compare it to the reference voltage, and then modify the voltage such that it is closer to the reference value. By doing this, voltage collapse in the network is lessened and the voltage stability of the network is improved. Depending on the type of compensation required at the buses, STATCOM can improve or reduce the voltage profile of the buses by adjusting the value of the firing angles/pulses of the STATCOM bridges. In this study, an ANN controller provides the control action needed by STATCOM to alter the firing angles/pulses of its bridges in order to appropriately address the problems of the network. The three-phase test network will be simulated under typical operating conditions in order to obtain ideal voltage profile values (0.95 to 1.05pu), as well as under conditions of significant load contingency in order to obtain bus voltage values below the acceptable limit of 0.95 at the weakest bus without STATCOM connected. Then STATCOM simulated once more while being linked to the three-phase test network. When the network is stressed by a significant rise in bus loads, the firing pulses/angles of the STATCOM are modified to maintain the voltage profile of the weakest bus within an acceptable range of 0.95pu to 1.05pu. The input and target training data are formed, respectively, by the voltage values obtained in the simulation without STATCOM and their corresponding firing angles/pulses in the simulation with STATCOM. For the STATCOM, an ANN controller model was created.

E) Three Phase Model of the Nigeria Transmission Grid Network

A modified three phase network of the 44-bus 330KV Nigeria transmission network was created and utilised as the test network by modelling some network segments into an equivalent network. To make the network less complicated and simpler to maintain, a scaled-down version was used. This was accomplished by modelling some network segments into a comparable network. Some network segments were replaced with similar network blocks that were configured and used from the Simscape library in Simulink/Matlab. While maintaining the same properties of the network, this strategy assisted in reducing the number of network components, including buses.

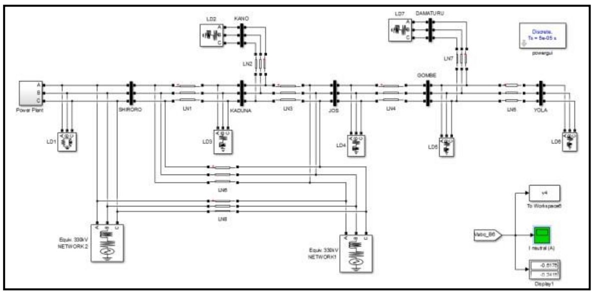

Figure 4: Reduced Version of the three Phase Simulink Model of the Nigerian 330KV Transmission Network.

SIMULATION RESULTS

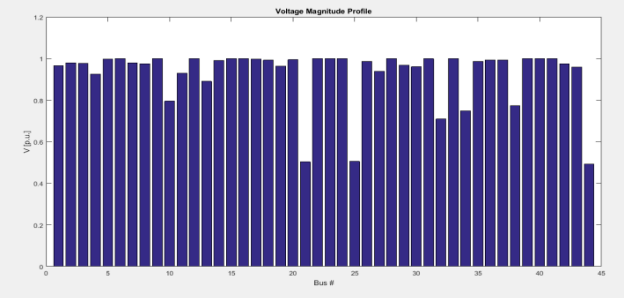

Figure. 5: Voltage profile plotted against bus number following load flow on the test network

Load flow studies were performed on the network to determine the voltage profile of each bus and to set up the setting for determining the voltage stability of the network using modal analysis. The outcome of the load flow shown in figure 5 indicates that the system is not voltage stable. This is due to the fact that some buses are already extremely close to the minimum permissible voltage threshold (0.95pu). Therefore, it may be necessary to provide some amount of compensation to keep the network from crashing when the system is under a lot of stress.

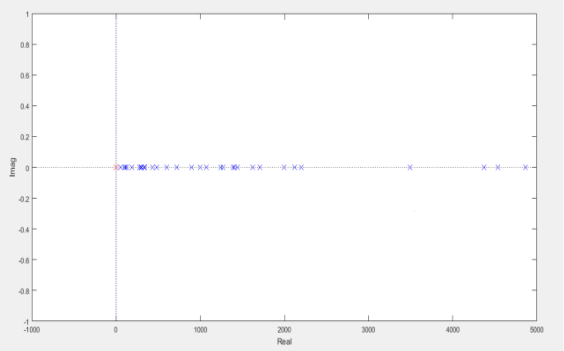

Figure 6: Plot of real and imaginary parts the system's eigenvalue for normal working condition.

After load flow studies were successfully carried out on the network using PSAT, modal analysis was also performed in the same environment. From the result shown in figure 6 it can be seen clearly that under normal operating condition without any contingency and compensation, the system recorded an eigenvalue with a negative real part. This confirms the earlier suspicion that the system is unstable with respect to voltage. This result implies that the system will experience a more severe voltage instability that could lead to voltage collapse when put under additional stress. The connection of a reactive power compensator is needed if the network's voltage stability is to be restored for the mitigation of possible voltage collapse during network contingency. An ANN controlled STATCOM was employed to effect reactive power compensation for the improvement of voltage stability and mitigation of voltage collapse in the test network (Nigeria 44-bus network) during stress condition occasioned by sudden increase in network loading. To achieve this, the load at each bus was doubled. The test network with doubled load was then simulated first without ANN controlled STATCOM connected. The ANN controlled STATCOM was then connected (as shown in figure 7) and simulated again. Figures 8 and 9 respectively present a graph of the peak voltage magnitude at the weakest bus (Yola) and the PV curves for an increase in load contingency case with and without STATCOM. In both figures, the red line represents the curve obtained for the case of contingency of increase in load with ANN controlled STATCOM not connected. On the other hand, the blue line represents the curve for the case of contingency of increase in load but with ANN controlled STATCOM connected to the test network.

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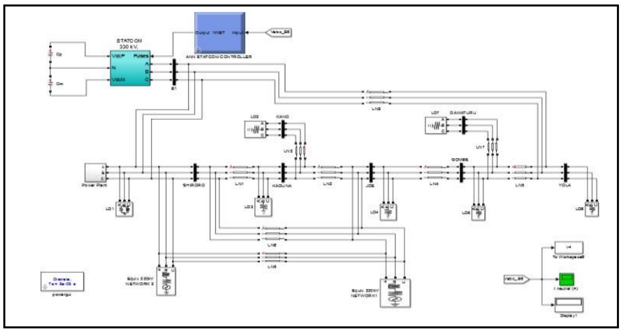

Figure 7: Test network with ANN controlled STATCOM connected during contingency of increase in load.

Figure 8 shows that peak phase voltage remains at 0.65pu all through for the case without connection of ANN controlled STATCOM but with ANN controlled STATCOM connected, the peak phase voltage was enhanced to 1.02pu. This represents an improvement of 56.9% in voltage profile and voltage stability.

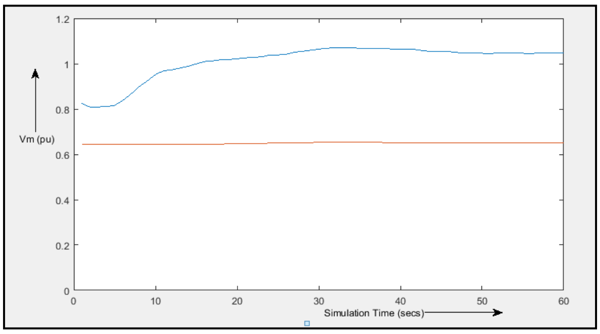

Figure 8: Plot of voltage magnitude against time for during increase in load contingency with and without ANN controlled STATCOM connected.

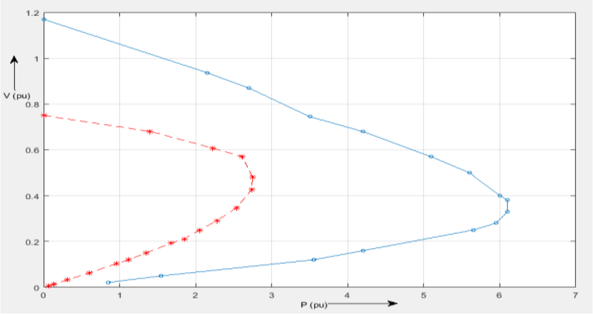

Figure 9: PV curves for the load gain contingency case with and without STATCOM

Percentage Point of voltage collapse mitigation margin (%PVCMM) as expressed in (Aneke *et a*l, 2020**)** can be computed as follows

$$\%PVCMM = \frac{P2-P1}{P1} x \frac{100}{1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where;

P_1= maximum power transferred at voltage collapse point without STATCOM connected.

P_2= maximum power transferred at voltage collapse point with STATCOM connected.

PVCMM = (6.1 - 2.748)/2.748

= 1.22

%PVCMM = 122%

RESULT AND DISCUSSION

From the results obtained it can be seen that when the network was stressed by doubling the loads at each bus, the connection of an ANN controlled STATCOM improved the voltage profile and stability of the network by 56.9% and extended the point of voltage collapse by 122% relative to the point of voltage collapse when STATCOM was not connected. The implication of this extension is improvement on the loadability of the network by 122% before voltage collapse can occur. This is an appreciable level of voltage collapse mitigation in the test network. The result obtained also shows that the ANN controlled STATCOM is intelligent enough to stimulate enough reactive power support during severe contingencies.

CONCLUSION

Analysis of results in this research showed that by extending the point of voltage collapse margin of the network by a factor of 1.22, voltage stability of the Nigeria 44-bus 330kV transmission power network was improved and voltage collapse mitigated in the network during a contingency of large increase in load on the network. This was achieved by connecting an ANN controlled STATCOM device across the most vulnerable bus (Yola). The ANN controlled STATCOM was able to dynamically provide sufficient reactive power support that increased voltage profile of the most vulnerable bus (and indeed other buses) to 1.02pu well above the minimum acceptable level of 0.95pu when the loads at the buses were doubled. This restored the network's voltage stability and extended the point of voltage collapse margin. It can be concluded that STACOM device made intelligent by ANN controller when connected across the most vulnerable bus improves the voltage stability and mitigates voltage collapse of a multi-bus network during contingency of large increase in load.

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