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ENHANCING THE VOLTAGE STABILITY OF THE NIGERIAN 330KV 28 BUS POWER NETWORK USING UNIFIED POWER FLOW CONTROLLER (UPFC) AND HIGH VOLTAGE DIRECT CURRENT (HVDC) DURING CONTINGENCY OF THREE PHASES FAULT

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Abstract

This research project is on the voltage stability enhancement of the Nigeria 330KV Power network using a parallel operation of Capacitor Commutated Converter based High Voltage Direct Current (CCC-HVDC) and Unified Power Flow Controller (UPFC). Power system disturbances caused by loss of generation, faults, switching actions, change in loads etc. lead to various degrees of voltage instabilities. The consequence of voltage instabilities in our Power networks can be severe. This is because it can lead to loss of loads, loss of generation and loss of generator synchronism, under-frequency and ultimately, voltage collapse. Imbalance in the reactive power supplied and the reactive power absorbed by the system has been identified as the key cause of voltage instabilities on our networks. High Voltage Direct Current and Flexible AC Transmission System (FACTS) are new technologies that employ modern Power electronic techniques in controlling transmission system parameters. These devices have been found to be very fast, flexible and effective in controlling active and reactive power, independently. In this research a FACT device, Unified Power Flow Controller (UPFC) and Capacitor Commentated Converted-based High Voltage Direct Current, working together were used to improve the voltage stability of the 28-bus Nigerian 330kV network during a contingency of three phase fault on the line. The UPFC and HVDC models and their respective neural network controllers were developed in Simulink Matlab utilizing resources from Matlab and Simscape libraries. Transmission network data obtained from Transmission Company of Nigerian (TCN) Osogbo and augmented with simulation data was used to train the ANN controllers. Result of simulations of the network models reveal that both UPFC and HVDC reasonably improved the voltage stability of the Nigerian network when a contingency of three phase fault was imposed on the network. The HVDC-UPFC system gave 144% improvement in voltage stability relative to a network without any device during a three phase fault situation. Judging from the high level of enhancement recorded in voltage profile and VPSM during three phase fault condition, it can be concluded that voltage stability enhancement offered by a parallel operation of UPFC and HVDC is the network is appreciable during three phase fault situation.

Keywords: Voltage stability, UPFC, HVDC, Voltage profile

1 Introduction

Disturbances are common in our power networks. These disturbances can come in different forms ranging from switching actions, change in load (loss or addition) and change in generator excitation to fault conditions. The effects of these various forms of disturbances in a power system can be devastating especially when the disturbances occur suddenly as is usually the case. It could result in loss of synchronism, progressive increase or sagging in voltage profile, severe under frequency and ultimately voltage collapse. The fragile and stressed nature of most power networks can make the system even more vulnerable to disturbances which could lead to these undesirable effects that can make our system unreliable. Using stability analysis of power system, one can determine the boundaries within which the system can safely operate (even in the face of some of these disturbances) and possible control actions needed to extend the limits of stability of the system so as to be able to bring the system back to normal operation even with disturbances of high magnitude. Under normal operation, a system should maintain steady voltage at all buses. With reference to an initial operating condition, Power system stability refers to a power system's capacity to regain an operating equilibrium state after undergoing a physical disturbance, such that keeping most system variables bounded, the system integrity is preserved [1]. From the above definition, we can infer that for a power system to remain stable, it should be able to adjust and operate successfully on encountering small and severe disturbances in the form of load changes, short circuits, loss of a generator, etc. An unstable system however, is not able to adjust and operate successfully in the face of physical disturbances. Such systems are characterized by a sustained increase in generator rotor angular separation, bus voltage sags and severe system outages.

Power system stability has continued to be a critical issue in maintaining a reliable electric power network considering that instability in power system operation will ultimately result in cascaded outages and system's inability to meet load demands at a given time. Though the increasing load demands, long-distance transmission lines and multiple power electronic devices are already posing serious challenges to power system stability [4] the electricity deregulation that has now been widely adopted by the power industry of many countries may present even more serious challenges in resolving stability issues in our power networks.

Different criteria can be used to classify power system stability. From the perspective of the physical presentation and mode of instability, three types of power system stability can be identified: Rotor angle stability, Voltage stability and Frequency stability. Looking at the time span of instability, two categories of power system can be identified: Transient and steady state stability. Another base for classifying power system stability is the size of disturbance. With reference to the size of disturbance, power system stability can be categorized into two: small disturbance and large disturbance stability [2]. Voltage stability shall be the main focus of this research paper considering that severe voltage instability easily lead to voltage collapse.

Imbalance between the quantity of reactive power absorbed by the system and the quantity of reactive power actually made available for the system has been identified as the major cause of voltage instability in a power network. This imbalance could be as a result of loss of loads, reactive power losses during transmission or limitations in reactive power generation. There is therefore need to develop an effective and efficient technique for keeping the required balance between consumed and generated active and reactive power in a network so as to ensure voltage stability.

Flexible AC Transmission System (FACTS) is a new technological application used in power systems. FACTS devices employ modern power electronic technology in controlling transmission system parameters. FACTS devices enhances existing transmission systems' power transfer capacity, minimizes line losses and cost of generation, give faster, reliable and flexible responses and in general improve the security and stability of a power network. Common FACTS devices include: Interface Power Flow, Static VAR Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), Unified Power Flow Controller (UPFC), Static Phase Shifter (SPS), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), etc [3]. Also, High Voltage Direct Current (HVDC) link is one of the most attractive means of ac transmission especially over long distances. Some situations exist where HVDC transmission technology is either the only or the most effective means of transmitting electric power over a distance. UPFC and HVDC have become very popular in power transmission system control due to their ability to offer independent control of active and reactive power. In this paper, a hybrid technique in which UPFC and Capacitor commutated converter based High Voltage Direct Current (CCC-HVDC) are connected in the same network is proposed for the optimum control of active and reactive power in the Nigerian 330kV network for voltage stability enhancement during contingency of three phase fault.

2 Voltage Stability

A voltage stable power system is one in which the voltages close to loads approach post disturbance equilibrium values, subject to a disturbance and given an operating state, the perturbed state is kept within stable post-disturbance equilibrium region of attraction [4]. Similarly given an initial operating condition, [1] defined voltage stability as the capacity of a power network to retain at all buses, constant voltages in the network after undergoing disturbances. From the above definitions, we observe that in the face of disturbances such as fault conditions, change in load or generator losses; a power network is said to have voltage stability if it is able to sustain approximately steady voltage at all buses. To do this end, voltage stability can be viewed as the property of a power network to sustain or restore balance between loads supplied and load demanded. When a system is unable to sustain or restore this balance in the event of a disturbance, instabilities may result in form of progressive and sustained voltage increase or decrease of some buses. This could cause loss of load in a network, tripping of transmission lines and other elements by their protective devices, thereby resulting in cascaded outages or voltage collapse [1]. These outages can cause some generators to lose synchronism and as such, rotor angle stability can be linked to sustained fall in bus voltage. As noted earlier, the imbalance between the quantity of reactive power needed for voltage support and the quantity of reactive power made available for the system has been identified as a major cause of voltage instability. The major causes of this imbalance are loss of loads and limitations in reactive power generation. Voltage instability can also manifest in form of sustained progressive over voltages in some buses of a power system if synchronous compensators and generators are prevented from absorbing excess reactive power due to the actions of excitation limiters [1].

3 Unified Power Flow Controllers (UPFC)

The unified power flow controller (UPFC) is one of the most popular of all FACTS devices. It was realized by combining the static series compensator (SSSC) and the static synchronous compensator (STATCOM) such that they are coupled through a common dc link. This is to permit a bidirectional flow of active power between the series output terminals of the SSCS and STATCOM. The key function of the UPFC is to control the real power and reactive power flow. This is achieved by injecting voltage in series with the transmission line. The effective control of reactive power and real power allows the transmission lines to be loaded closer to their thermal limits and can help to enhance the stability of the system [5]. A schematic diagram of a UPFC sourced from [5] is shown in figure 3.1.

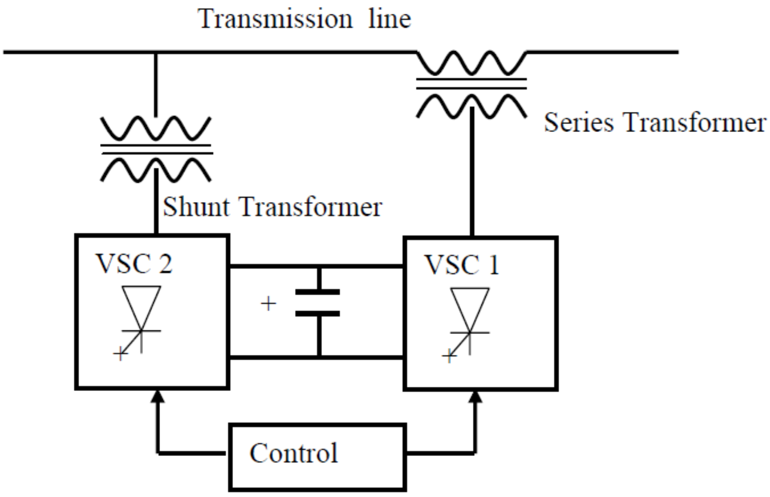

Fig 3.1: Schematic diagram of a Universal power flow controller (UPFC) [5]

There are two branches in the schematic diagram of UPFC of fig. 3.1.: the series branch and the shunt branch. The voltage source converter (VSC-1) in the series branch injects voltage in series with the line through the series transformer. The ability of the series branch of the UPFC to inject a voltage with variable magnitude and phase makes real power exchange with the transmission line possible. The availability of a power source at the DC terminals facilitates the supply or absorption of real power at steady state by the UPFC as a whole [5].

The independent control of real and reactive power at the UPFC circuit is made feasible by regulating the voltages of the DC- link capacitor and also by adjusting both the modulation index and the phase angle of the input inverter.

4 Capacitor Commutated Converter based High Voltage Direct Current (CCC-HVDC)

Capacitor Commutated Converter based HVDC (CCC-HVDC) system evolved as a result of an effort to improve on the power control capacity of Current Source Converter based HVDC (CSC-HVDC) system and reduces its inherent high risk of communication failure, while keeping bulk transmission cost low. The CCC-HVDC is a modification of CSC-HVDC. This modification is the addition of a series capacitor between the transformer and the valves of each phase.

Additional series commutation capacitors make available additional commutation voltage that makes it possible for the inverter to be operated at a small firing angle and small extinction angle respectively. As a result of this, the converters' reactive power consumption are reduced likewise the size of the fitter capacitance [6]. This improves the overall stability of the system; the CCC-HVDC system is most suitable for networks whose short circuit ratios (SCR) are lower than that of the HVDC converters. One major challenge of the CCC-HVDC technology is the increase in high ac harmonic caused by a reduced commutation time and also reduced overlap angle. This challenge can be overcome by increasing the AC filter rating [6]. The advantage derived from the CCC technology lies in the fact that the converters are much less dependent on the AC network strength for the successful commutation of the valves. As a result, commutation failures due to network disturbances are highly reduced [6].

A schematic diagram of a Capacitor commutated converter based HVDC (CCC-HVDC) sourced from [6] is shown in figure 4.1.

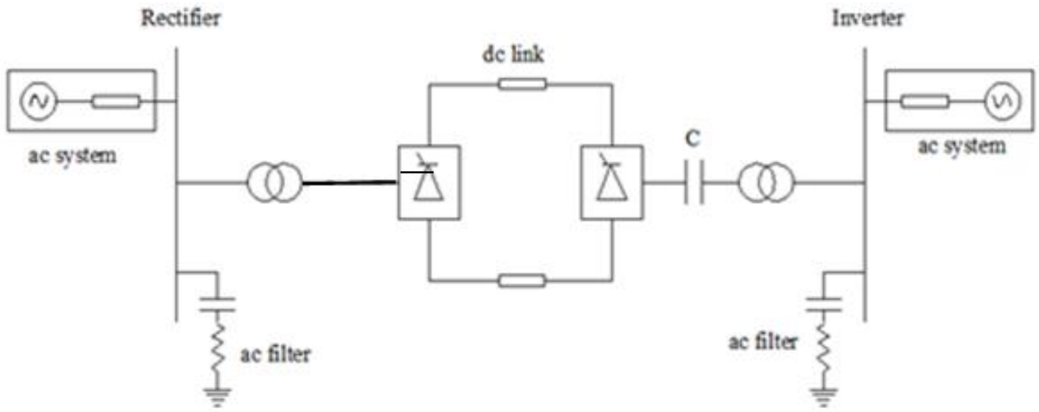

Fig 4.1: Schematic diagram of a CCC-HVDC. [7]

5 Method

To improve the voltage stability of the Nigerian power network; it is important to first identify the weak buses. With this information, one is in a better position to know which buses require compensation and how best the compensation will be done. To identify the weak buses, a power flow study needs to be run on the Network. Here, a test case of the Nigerian 330KV 28-bus system will be used. Due to its advantage of overcoming convergence issues at critical points, continuation power flow technique is for the identification of weak buses. Result of the continuation power flow run on the network revealed that Yola bus is the weakest bus. Gombe, Jos and Kaduna buses are the other highly vulnerable buses identified in the network.

UPFC and Its Control Strategy

The Unified power flow controller (UPFC) consists of two Capacitors with turn-off capability: The semiconductor device of choice in this design is a gate turn off thyristor (GTO). A 24-pulse gate turn off thyristor is used in implementing the two converters (shunt and series) needed in this modelling. As proposed in [7], the aim of the series converter is to produce an AC voltage whose phase angle and magnitude can be controlled. This ac voltage will be injected into the transmission line at fundamental frequency for the exchange of real and reactive power through the series transformer at the ac terminals. While the generation or absorption of reactive power by each of the converters occurs independently without flowing through the dc link; the real power at the dc terminals is provided by the shunt converter. Equations 5.1 and 5.2 shows that the real power (at the dc terminals) from the shunt converter and the injected ac voltage (at ac terminals) can be controlled by adjusting the firing angles ∝ and ß of the shunt and series converters respectively.

$$\upsilon_{ish} = \sqrt{2}V_k \text{ Sin}(wt{+}\propto) \quad (5.1)$$

$$\upsilon_{ise} = \sqrt{2}\ V_{ise}\, Sin\ (wt + ß) \quad (5.2)$$

Where υ_{ish} is the shunt converter sinusoidal voltage and V_k is its corresponding rms value. Similarly, υ_{ise} is the series converter sinusoidal voltage and V_{ise} is its corresponding rms value.

CCC-HVDC and the Control Strategy

The HVDC link is basically made up of a rectifier, an inverter and a dc link. A capacitor commutated converter based HVDC link (CCC-HVDC) has additional capacitor provided between the converters and the transformers. The basic idea in this concept is that the capacitors contribute to the valve commutation voltage. This contribution makes it possible to operate the CCC-HVDC with much lower reactive power consumption compared to the conventional HVDC link. The reactive power demand of the rectifier has been found by [8] to be increasing with converter firing angle "∝", while the inverter reactive power demand also increase with the converter extinction angle "γ"

$$Cos\,\emptyset = {}^{1}/_{2}\,[\cos\propto\ +\cos(\propto\ +\mu)] \qquad (5.3)$$

$$Cos\,\emptyset = {}^{1}/_{2}\,[\cos\gamma\ +\cos(\gamma\ +\mu)] \qquad (5.4)$$

From equations 5.3 and 5.4, it is evident that to operate the system at a reasonable high power factor and minimum reactive power demand, the rectifier firing angle "$\propto$" and the inverter extinction angle "γ" has to be at their possible minimum values. This is the HVDC control strategy.

By varying the firing angles of the rectifier and the inverter, both active and reactive power control of a network linked by CCC-HVDC can be achieved such that voltage stability of a weak AC network can be enhanced by connecting it to a more stable one via a CCC-HVDC link.

UPFC and CCC-HVDC Neural Network Control

The neural network fitting app was used in this project. It has the capacity to map between a data set of numeric inputs and outputs with very high degree of accuracy, if properly trained with adequate volume of data. In modeling the HVDC and UPFC neural network controllers, voltage profiles of vulnerable buses were collected. This data set formed the input to the developed HVDC and UPFC models. Adjustments in the firing angles of the converters of the devices were made until the weak buses attained enhanced voltage profiles. The corresponding values of measured and reference parameters that gave the stable results were recorded for all the converters. The corresponding triggering pulses for the converters were also recorded. The reference and measured values formed the input of the neural networks while their corresponding triggering pulses formed the output or target of the neural networks during the training.

The UPFC ANN controller has 19 inputs including 10 variables from the shunt side and 9 variables from the series side. The shunt input variables are the three phase voltages from the shunt side, V_{abcsh}, three phase current from shunt side, I_{abcsh}, shunt side reference voltage, V_{refsh}, shunt side reference reactive power, Q_{refsh}, and the shunt side DC voltages V_{dcsh1} and $V_{dcsh2.}$ The series input variables are the three phase voltage from the series side, V_{abcse}, three phase current from series side, I_{abcse}, series injected voltage, V_{injse}, and the series side dc voltages V_{dcse1} and $V_{dcse2.}$

The CCC-HVDC has two ANN controllers, one for the rectifier and the other for the inverter. The rectifier Artificial neural network (ANN) controller has six inputs including the measured three phase bus voltage$V_{ar},\ V_{br}\ and\ V_{cr},$ measured DC voltage and current, $(V_{dr}\ and\ I_{dr})$ and the voltage reference, $V_{refr.}$ Correspondingly, the inverter ANN controller has six inputs including: $V_{ai},\ V_{bi}\ ,V_{ci},$ I_{di},$V_{di}$and V_{refi} . Both the rectifier and the inverter are made of twin bridges. Each bridge is triggered by six pulses. As a result, the rectifier has 12 outputs representing to 12 pulses for the two bridges. The inverter also has 12 outputs. The simulink models of the created UPFC ANN controller and rectifier ANN controller connected to the test network is shown in fig. C.

The idea behind this research is to show that UPFC and CCC-HVDC working together in a network driven by their ANN controllers can improve the network's voltage stability during a contingency of three phase fault.

6 Evaluation of the System Performance

The performance of the HVDC-UPFC system in enhancing the voltage stability of the test network during three phase fault shall be evaluated by assessing the improvement on Voltage Profile Stability Margin (VPSM) of the weakest bus given by connecting the devices to the network during three phase fault.

The voltage profile stability margin (VPSM), here, is a measure of the improvement in voltage profile caused by connecting the compensating device to the network while keeping the network at real power of P_{max}. Meanwhile P_{max} is defined as the maximum network real power loading (at critical point or just before voltage collapse) when no

compensating device is connected. VPSM is expressed as a fraction of the voltage profile at P_{max} loading with no compensating device connected.
To obtain VPSM given by the device (HVDC-UPFC), the voltage profile (V_{cn}) at P_{max} is first obtained when the device is connected. HVDC-UPFCis then connected and the voltage profile (V_{cd}) obtained at P_{max}. The network reactive power is kept constant at its normal loading value throughout the process. Mathematically, VPSM can be expressed as follows:

$$VPSM = \frac{V_{cd} - V_{cn}}{V_{cn}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.1)$$

7 Simulations and Results and discussion

The Nigerian 330kV 28-bus, single line network, modelled in PSAT/Simulink MATLAB is presented in appendix A. The developed model served as the data file during the running of continuation power flow on the network in PSAT. However, for purposes of simulating the network with the compensating devices (HVDC and UPFC) connected, a condensed equivalent three phase circuit of the 28-bus network was developed. This equivalent model showing the weakest buses but with the compensating devices not connected is shown in appendix B while the equivalent model showing the weakest buses with the compensating devices (HVDC and UPFC) connected is shown in appendix C. A three phase fault block is connected to the models of appendix B and C to introduce three phase fault in the network during simulation. The results of simulating the network model of appendix B and appendix C are given in figs 7.1 and 7.2 respectively.

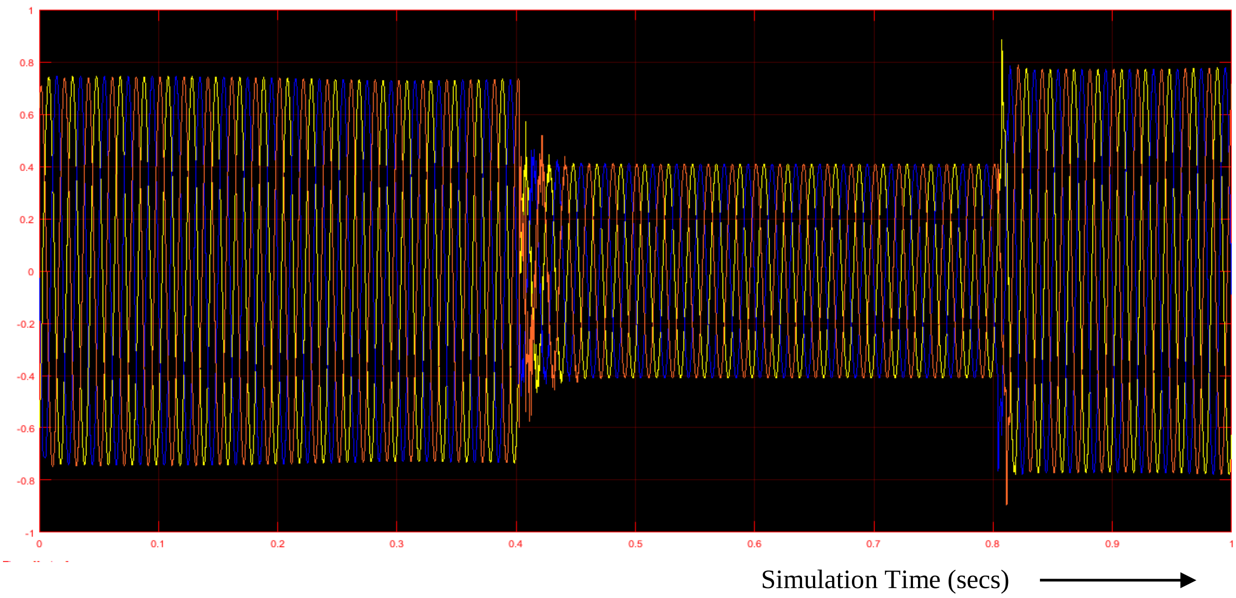

Fig.7.1: Voltage response for Yola bus at $P_{max}$with a three phase fault with no device connected

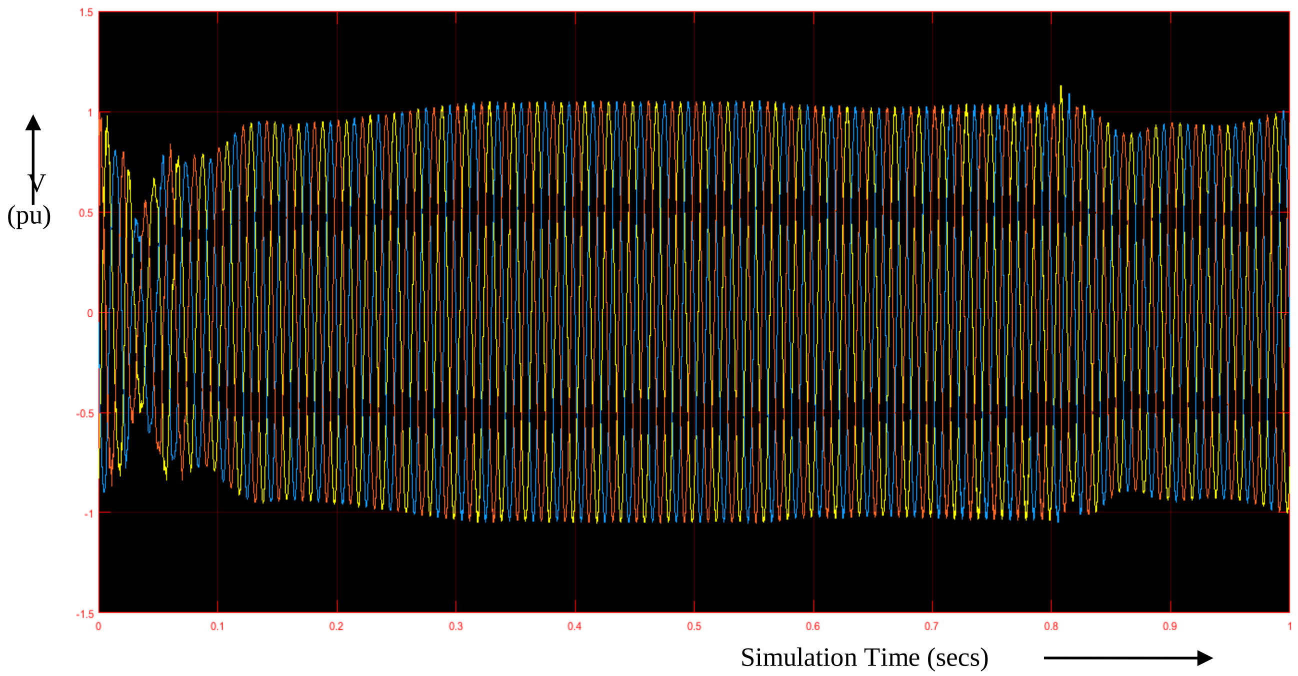

Fig.7.2: Voltage response for Yola bus at P_{max} with a three phase fault and with UPFC and CCC-HVDC connected.

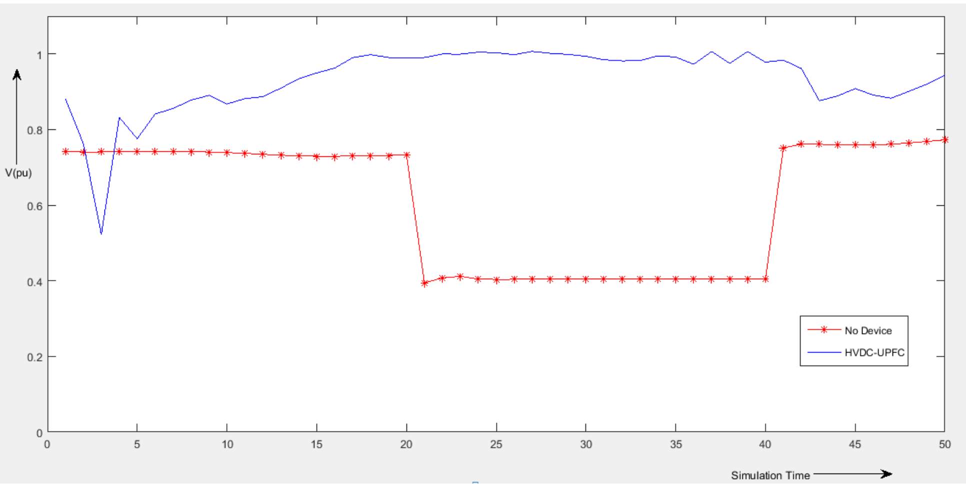

Fig. 7.3: A graph of peak phase voltage profiles (with and without devices) against simulation time at Yola Bus with three phase fault contingency imposed on the network

From fig 4.73, it can be seen that the three phase fault introduced in the network between the 20th and 40th second reduced to the voltage profile to about 4.1pu. On the other hand, the connection of the HVDC-UPFC system to the network did not only mitigate the impact of the three phase fault but also enhanced the voltage profile to approximately 1.0pu (the optimum voltage profile).

Table 7.1: Voltage profile of the weakest bus, Yola at critical during three phase fault

Contingency	No Device	HVDC-UPFC
Three Phase Fault	0.41	1.00

$$\text{VPSM} = \frac{1.00-0.41}{0.41} = 1.44 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7.1)$$

Table 7.1 and equation 7.1 show that the HVDC-UPFC system gave a 1.44 VPSM and a 144% improvement in voltage stability during a three phase fault contingency.

8 Conclusion and Recommendations

It can also be concluded that relative to the network with no compensating device connected, HVDC-UPFC system peformed appreciably well in enhancing voltage stability of the test network during three phase fault condition. Based on the findings in this research, it is recommended that FACTS devices like UPFC and the HVDC technology be installed in our transmission networks at the identified vulnerable buses as a way of enhancing the stability of the network in the face of aged equipment, inadequate generating and transmitting capacities and other external contingencies. The high effectiveness of ANN controllers recorded in this research points to the efficacy of Neural network controllers and shows that it can have a wider applications in power systems. It is recommended that further research be done on how to effectively apply neural network controllers in power systemprotection and control.

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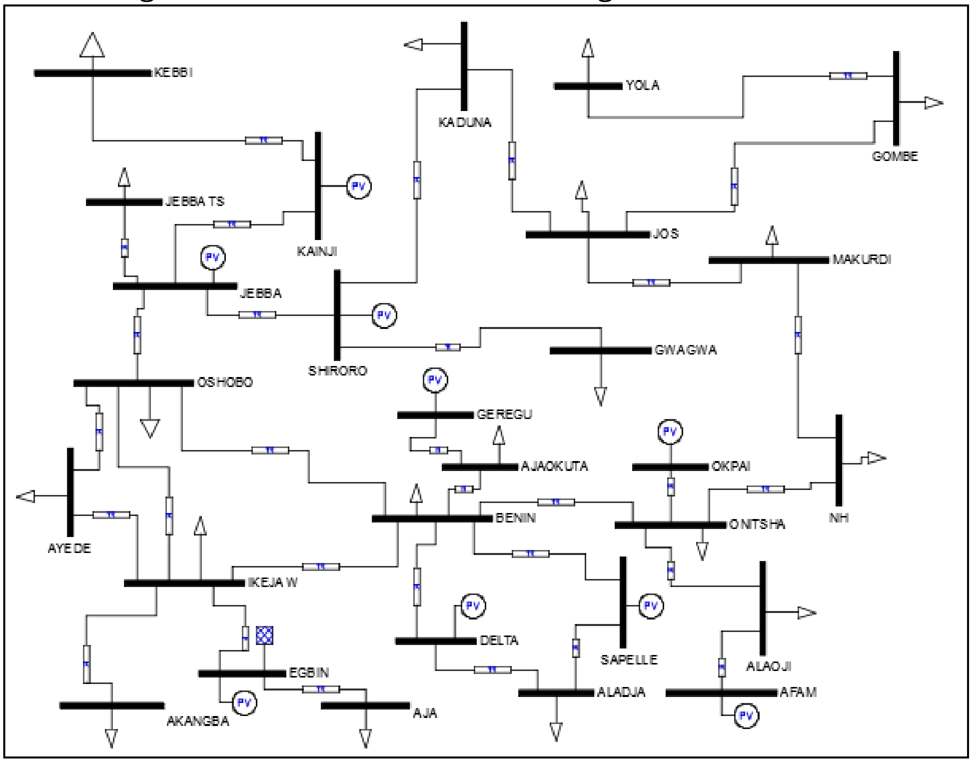
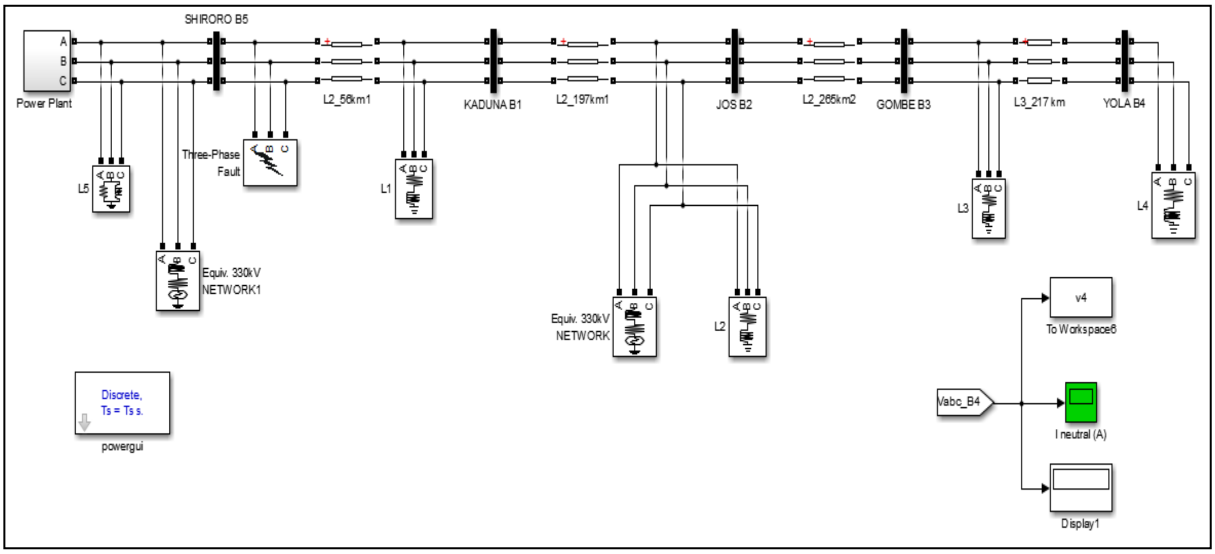
APPENDIX A

Single Line Simulink model of the Nigerian 330kV 28-bus



APPENDIX B

Equivalent Network Model Showing Yola, Gombe, Jos and Kaduna Buses with Three Phase Fault with No Device Connected



APPENDIX C

Equivalent Network Model Showing Yola, Gombe, Jos and Kaduna Buses with Three Phase Fault with UPFC and CCC-HVDC Connected