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NEURAL NETWORK BASED VOLTAGE STABILITY IMPROVEMENT OF THE NIGERIAN 330KV POWER NETWORK USING UNIFIED POWER FLOW CONTROLLER (UPFC) AND HIGH VOLTAGE DIRECT CURRENT (HVDC) DURING CONTINGENCY OF LARGE LOAD GAIN.

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Abstract

This paper presents the neural network-based voltage stability improvement of the Nigeria 330KV Power transmission network using a Unified Power Flow Controller (UPFC) and High Voltage Direct Current (HVDC). The impact of voltage instabilities in our power networks can be damaging. Load changes, loss of generators, amongst other contingencies, can introduce voltage instability in the networks. In this research, a parallel operation of the Unified Power Flow Controller (UPFC) and High Voltage Direct Current (HVDC) is employed to enhance the voltage stability of the Nigerian network under a contingency of large load gain. HVDC and UPFC have become very attractive in network compensation due to their ability to independently control real and reactive power in a network. Simulink models of the test network, the UPFC and HVDC, were developed in Matlab for simulation. Neural network controllers designed and implemented in Simulink Matlab effectively controlled the devices to achieve the desired result when the network was simulated. Results obtained from simulations revealed that relative to when the devices were not connected to the network, a parallel operation of HVDC and UPFC improved the voltage stability of the network by 43.8%. It can be concluded that the operation of HVDC and UPFC together in a power transmission network is effective in enhancing voltage stability of the network during a contingency of large gain in load.

1 Introduction

Due to frequent disturbances, power system stability is continuously under threat. The consequences of instabilities in a power system can be damaging both on the network itself and the users (electric power

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consumers). Sustained instabilities in a power system can make some generators lose synchronism, lead to loss of generators and loads, cause under frequency, and ultimately cascade voltage collapse (blackouts). Voltage collapse or blackouts on our 330kV systems imply that the majority of the electric power consumers will have frequent and long power outages. This will hurt the standard of living of the domestic consumers and the productivity of the industrial consumers. The overall effect of frequent voltage collapse caused by voltage instabilities is reduced national development and poor standard of living of the Nigerian citizens. [1] defined a voltage stable power system as one in which the voltages close to loads approach post disturbance equilibrium values, and subject to a disturbance and given an operating state, the perturbed state is kept within stable post-disturbance equilibrium region of attraction. From the above definition, if the voltages at buses near loads are not kept within equilibrium region after a disturbance like gain in large load, voltage instability will result. Voltage instability is one form of instabilities that can easily cause voltage collapse in a network; hence the need to ensure that voltage stability margin is always kept at an optimum level in our power networks. The goal of this research work is to improve the voltage stability of the Nigerian power system so that the overall power systems' stability, security and integrity is also improved. This apart from protecting the power network will ensure that both domestic and industrial/commercial consumers of electricity enjoys good quality and reliable power supply that will increase productivity and eventually translate into socio-economic development of our nation. To enhance the voltage stability of the Nigerian 330kV network during contingency of large load gain, this paper proposes the use of a hybrid technique that will combine a FACTS device; Unified Power Flow Controller (UPFC) and Capacitor commutated converter based High Voltage Direct Current (CCC-HVDC) to produce an optimum control of active and reactive power in the network. The choice of UPFC and HVDC is formed by their ability to independently control real and reactive power in a network. These devices use modern power electronic technologies and as a result are fast, robust, flexible and very effective in power flow controls [2].

2 LITERATURE REVIEW

Unified Power Flow Controller (UPFC)

Among all the FACTS devices, UPFC is the most resourceful and flexible. It can perform the functions of Static Series Compensator (SSSC), Static Synchronous Compensator, Thyristor Switched Capacitor and thyristor controlled reactor as well as combining the features of the above devices to offer additional flexibility in the control of power flow in a network [3]. By injecting voltage in series with the transmission line the UPFC is able to control real and reactive power flow in the network. By varying both the magnitude and phase angle of the voltage, thermal limits of transmission line loading can be extended for an improved stability of the network [3]. As shown in fig 2.1, the UPFC consist of two voltage source converters linked through a common DC capacitor. The voltage source converters are equipped with modern semiconductor devices with turn-off ability. Each of the two converters is connected to the AC network via coupling transformer. One is connected in series with the AC network to form the series branch while the other is connected in shunt with the AC network to form the shunt branch [4]. The voltage source converter of the series branch injects a series voltage (adjustable in magnitude and phase) through the coupling transformer into the transmission line and that way exchanges active and reactive

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power with the AC network. The needed real power at the DC terminal is provided by the shunt converter. The common DC link allows real power flow between the device's shunt and series terminals. On the other hand reactive power is generated or absorbed independently at each end [4]. A schematic diagram of a UPFC system presented by [5] is shown in fig 2.1.

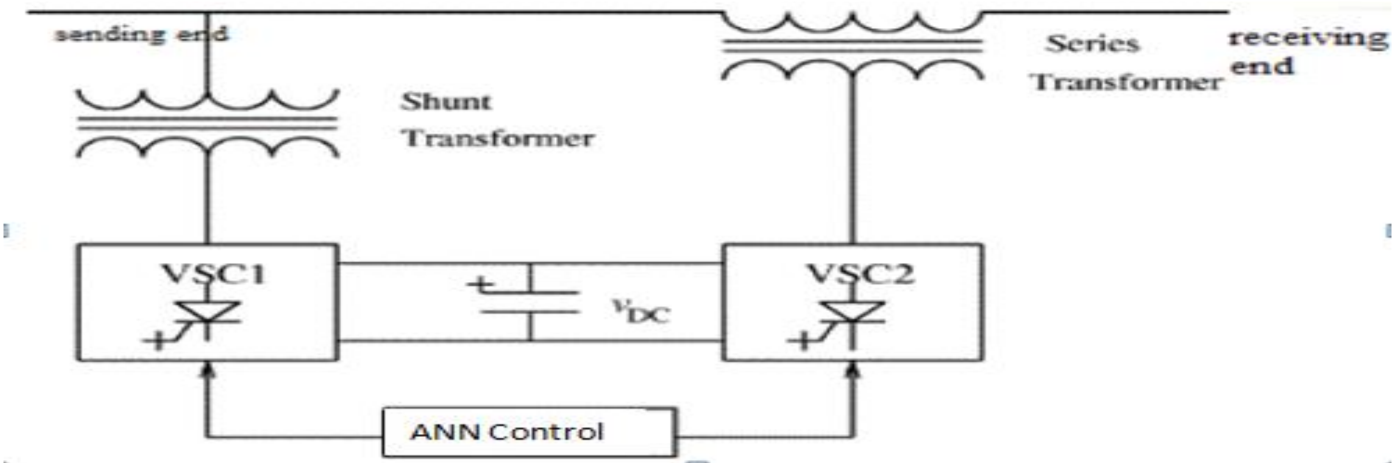

Fig 2.1: Schematic diagram of a Universal power flow controller (UPFC) [5]

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

AC transmission has some inherent advantages in power transfer. Some of them include: ability to be transformed to different voltage levels, high capacity for long distance power transmission using transformers, Cheaper and more robust motors, and the advantage provided for circuit breakers by the natural current zeros that occur twice per cycle in an AC system. [6]. Despite these merits, DC transmissions remain very relevant. 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. [6] listed these scenarios to include: Electric Power transmission through cables, Long-distance bulk Power transmission, Power transmission involving two unsynchronized interconnected system: Another advantage of HVDC link over DC transmission is its ability to damp oscillation two to three times better than reactive shunt compensators [7]. They are current source converter (CSC) is a popular technology in HVDC implementation. The CSC maintains the DC current at the same polarity and as such the power flow direction through the converter is determined by the DC voltage polarity. CSC's are designed with semi-controllable switches such as thyristors, in which current interruption is only determined by the zero ac voltage zero crossing. The CSC produces current and voltage harmonics on the AC side needing large ac filters to remove [8]. Despite its successful application, it was observed by [7] that commutation failure at the inverter station occasioned to disturbances in the AC systems is a key weakness suffered by the CSC technology. In an effort to improve on the power control capacity of CSC-HVDC system and reduce its inherent high risk of communication failure, while keeping bulk transmission cost low, the Capacitor-commutated converter (CCC) based HVDC system was

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developed. The CCC-HVDC is a modification of CSC-HVDC. This modification is the provision of a series capacitor between the transformer and the valves of each phase on the inverter side of the HVDC link. It was noted by [9] that the additional series commutation capacitors provided an extra commutation voltage that makes it possible for the inverter to be operated at a small firing angle. As a result of this, the converters' reactive power consumption are reduced likewise the size of the fitter capacitance. This improves the overall stability of the system; the CCC-HVDC system is most suitable for networks whose short circuit ratio (SCR) is lower than that of the HVDC converters. 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 with much lower reactive power consumption compared to the conventional converter [10]. Furthermore, in terms of voltage stability, CCC gives a more robust and stable dynamic performance of the inverter station, especially when inverters are connected to weak AC systems and/or long DC cables. Increased commutation margins can be achieved, without increasing the reactive power consumption of the converter station. This is done by reducing the capacitance of the commutating capacitors in order to increase their contribution to the commutation voltage. A schematic diagram of a CCC-HVDC presented by [12] is shown in fig 2.2.

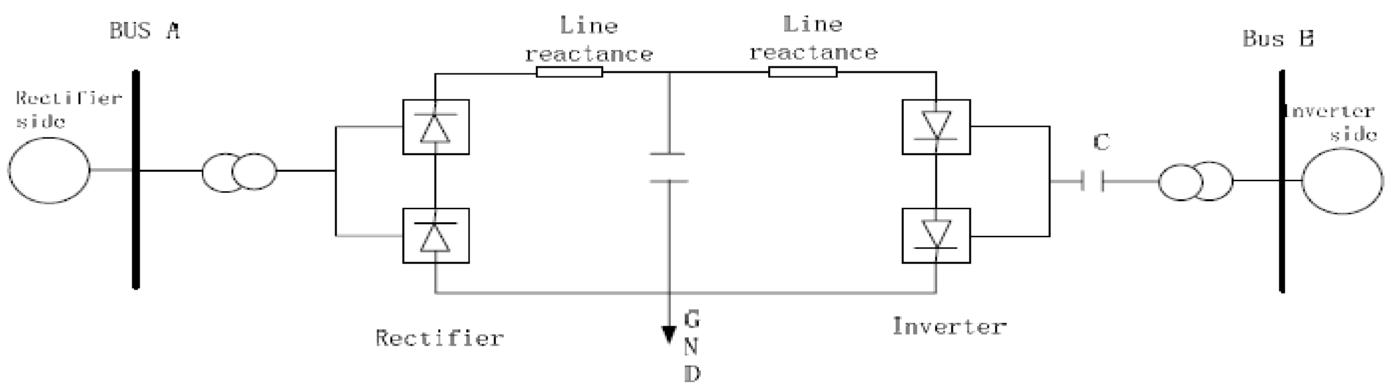

Fig 2.2: Schematic diagram of a CCC-HVDC. [12]

ARTIFICIAL NEURAL NETWORK (ANN)

Artificial Neural network was defined as an information-processing system having similar characteristic performance with the biological neural networks. Four assumptions upon which artificial neural networks can be developed as a generalization of mathematical models of the biology of human cognition was identified by [13]. These assumptions are:

i. That processing of information occurs in Neurons and that these neurons are many.
ii. That signals move between neurons via connection links.
iii. That there is an associated weight for each connection link and that this weight multiplies the transmitted signal in a typical neural network.
iv. That to determine its output signal; each neuron have to apply to its net input, an activation function.

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A neural net is made up of a large number of basic elements called cells, neurons nodes or units. They are simple processing elements in the network. A directed communication link connects the neurons to one another and each link is associated with a weight. Architecture (Pattern recognition between neurons); training Algorithm (methods of weight determination on links) and activation functions are key processes that characterize the neural network. The weights on the connections represent the information the network uses to resolve a problem [13]. Every neuron possesses an internal state defined as its activity level or activation. This activity level is a function of the input received by the neuron. A neuron can only send out one signal at time. However, a signal released by a neuron is usually received by several other neurons. A typical signal of a neuron that is broadcast to other neurons is its activation [13]. Consider for instance a neuron Y (shown in Fig 2.3) that receives signals from neurons X_1, X_2 and X_3. The output signals (activations) of these neurons as presented in [13] are x_1, x_2 and $x_3$respectively. The weight on the links between Y and X_1, X_2 and X_3 are respectively w_1, w_2 and w_3. The sum of the weighted signals from neurons X_1, X_2 and X_3 forms the net input, y-in to the neuron Y.

$$y - in = w_1 x_1 + w_2 x_2 + w_3 x_3 \qquad (2.1)$$

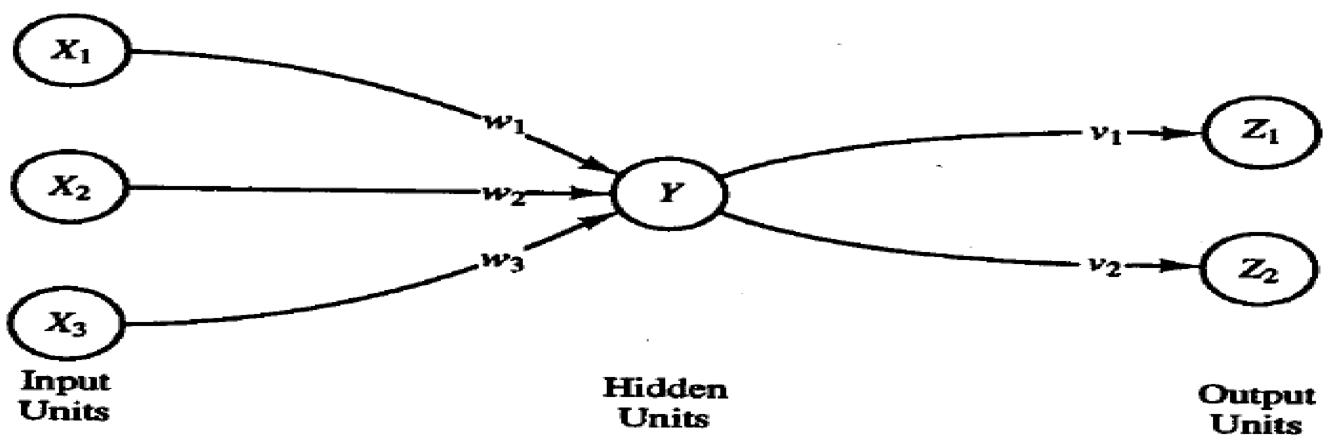

Fig.2.3: Schematic diagram of a simple neural network [13]

The Neuron Y will now have an activation y given by some function of the net input to Y. The logistic sigmoid function is a good example:

$$F(x) = \frac{1}{1+\exp(-x)} \qquad (2.12)$$

Consider again Fig 2.3 where Neurons Z_1 and Z_2 have been connected to Y via links with weights v_1 and v_2 respectively. Even though Y sends its signal y to Z_1 and Z_2, the signal values received by Z_1 and Z_2 will depend on the weights v_1 and v_2. A global view of the system of fig 2.3 will show it as one with input units X_1, X_2 and X_3 and output units Z_1 and Z_2 with Y as the hidden units. Neural nets with hidden units and nonlinear activation function can solve more problems than ones without hidden units. Systems with hidden units are however more difficult to train [13].

REVIEW OF RELATED WORKS

[14] Studied the power flow analysis of Nigerians 330kV network using MATLAB. They discovered that the existing 31-bus, 11 Gens, 6000MWinstalled capacity and 4,889km transmission grid network looked scanty, fragile, and lacked the capacity to provide adequate reliable electric power for the Nigerian consumers. The study tried to investigate the impact of the proposed 49-bus, 17 generators, 10,000 MW, 9156km transmission line grid network on the systems stability and reliability. They observed however, some deficiencies in voltage level and power flow in some buses. This was attributed to long live and low power consumption in the Northern areas. The affected single lines were replaced with double lines while the affected bus voltages were stabilized by introducing reactive power compensators. [15] Worked on the use of STATCOM to improve the voltage profile of the North-East 330kV power system in Nigeria. The Nigerian power network is characterized by poor fragile equipment, poor control and dispatch infrastructure, low voltage profile, high transmission losses and frequent collapses especially in the northern region, hence the need for adequate reactive power organization. Their technique in improving the system stability involved running a load flow of the Nigerian grid system at contingency with and without the modelled STATCOM so as determine the effect on the bus voltage profile improvement after optimizing using the STATCOM model using ant colony technique. Result and analysis of simulation carried out on the faulty bus showed an improvement on the voltage stability of the system [14]. [16] Studied power systems voltage stability improvement using static VAR Compensator (SVC). They observed that FACTS devices (SVC, TCSC, TCPS, STATCOM, SSSC, UPFC and IPFC) respond instantaneously and do not have issues of mechanical tear and wear since they are made up of solid semi-conductor components. Their paper studied the impact of static VAR Compensator (SVC) in stabilizing power systems voltage using Nigerian 28-bus 330KV using Simulink /MATLAB as their environment. The SVC was connected as a configuration of thyristor controlled reactor fixed capacitor (TCR-FC). Using a transmission line model extracted from the Nigerian 28-Bus system, they arrived at mathematical model that minimizes the voltage drop between two buses by keeping the voltage at one of the buses constant and adjusting the reactive power at the other bus [16]. [17] Developed a new control scheme for a CCC-HVDC with an inverter operating with constant alternating voltage. The main objective of the work was to propose a new control strategy that can be used for a CCC-HVDC. In the new arrangement, the inverter is to emulate the operation of a VSC such that both active and reactive power can be independently controlled. Their studies showed a significant reduction in the interaction between the inverter and the connected ac network. The study also proved that it is possible to operate the inverter into an almost passive ac network using the proposed new scheme. The result of the simulation showed satisfactory operation of HVDC transmission with the inverter working into a network with a short circuit ratio as down as 0.2 [17].

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3 Method

Continuation power flow was first executed on the Nigerian 330KV 28-bus power transmission network. The result was used to identify the weak buses. The choice of continuation power flow is to overcoming the non-

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convergence issues at critical points experienced when conventional power flow techniques are used. Yola bus was found to be the weakest bus while Gombe, Jos and Kaduna buses were also found to be highly vulnerable in the network.

UPFC and HVDC Control Strategy

The role of the series converter is to generate an AC voltage whose phase angle and magnitude can be controlled. This AC voltage will be injected through the series transformer into the transmission line at fundamental frequency for the exchange of real and reactive power at the ac terminals. Equations 3.1 and 3.2 proposed by [17] shows that the injected AC voltage (at AC terminals) and the real power (at the dc terminals) from the shunt converter can be controlled by adjusting the firing angles ß and ∝ of the series and shunt converters respectively.

$$\upsilon_{ish} = \sqrt{2}V_k \text{ Sin}(wt+\propto) \quad (3.1)$$

$$\upsilon_{ise} = \sqrt{2}\, V_{ise} \text{ Sin } (wt + ß) \quad (3.2)$$

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.

Capacitor commutated converter based HVDC link (CCC-HVDC) has additional capacitor provided between the converters and the transformers. The basic additional 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 inverter reactive power demand and the rectifier reactive power demand increases respectively converter extinction angle "γ" and converter firing angle "∝" [18],

$$\text{Cos } \emptyset = {}^{1}/_{2} [\cos \propto + \cos(\propto + \mu)] \quad (3.3)$$

$$\text{Cos } \emptyset = {}^{1}/_{2} [\cos \gamma + \cos(\gamma + \mu)] \quad (3.4)$$

As proposed [18] equation 3.3 and 3.4 shows that to operate the system at a minimum reactive power demand and reasonable high power factor, the inverter extinction angle "γ" and the rectifier firing angle "∝" should be kept at their possible minimum values. By adjusting the rectifier and the inverter firing angles, both active and reactive power networks linked by CCC-HVDC can be effectively controlled.

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. The UPFC ANN controller has 19 inputs including. The three phase voltages from the shunt side and the series end (V_{abcsh}, V_{abcse},), three phase current from shunt side and the series end (I_{abcsh} , I_{abcse}), shunt side reference voltage, V_{refsh}, shunt side reference reactive power, Q_{refsh}, shunt side DC voltages (V_{dcsh1} and V_{dcsh2}), series side DC voltages (V_{dcse1} and V_{dcse2}) and the series injected voltage, V_{injse}. The system is equipped with two HVDC ANN controllers, one for the rectifier and the other for the inverter. The rectifier Artificial neural network controller has six inputs including the measured three phase bus voltage, V_{abcr}, 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_{abci}, I_{di}, V_{di} and V_{refi} . The rectifier ANN controller has 12 outputs representing 12 pulses for the two bridges of the rectifier. Both

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the rectifier and the inverter are made of twin bridges. Each bridge is triggered by six pulses. The inverter also has 12 outputs. This research is basically to show that a parallel operation of UPFC and CCC-HVDC in a network controlled by their ANN controllers can enhance the network's voltage stability during a contingency of sudden gain of large load.

4 Evaluation of the System Performance

To evaluate the performance of the HVDC-UPFC system in improving the voltage stability of the test network during a contingency of sudden gain in large load, there is need to assess the level of enhancement in Voltage Profile Stability Margin (VPSM) of the weakest bus offered by the parallel operation of HVDC and UPFC in the test network during a contingency of sudden gain of large load [2]. 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 [2]. The voltage profile stability margin (VPSM) is obtained by first determining the voltage profile (V_o) at P_{max} with no compensating device connected. The voltage profile (V_d) is then obtained at P_{max} when HVDC-UPFC is connected to the network. The network reactive power is kept constant at its normal loading value throughout the process. Mathematically, VPSM can be expressed as follows:

$$\mathrm{VPSM} = \frac{V_d - V_o}{V_o} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.1)$$

5 Simulations and Results and discussion

Single line simulink model of the Nigerian 330kV 28-bus implemented in PSAT/Simulink MATLAB is shown in appendix A. Using the developed single line model as the data file, continuation power flow was run on the network using power system analysis tool (PSAT). This helped in determining the weakest buses. 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. Appendix B shows this equivalent model with the weakest buses but with the compensating devices not connected while appendix C presents the equivalent model with the weakest buses after the compensating devices (HVDC and UPFC) have been connected. The contingency of gain in large load is created by connecting a relatively large load (800 MW) to the network through a circuit breaker at Shiroro bus. The circuit breaker is then set to add the load to the bus for a given period during simulation. The results of simulating the network model of appendix B and appendix C are given in figs 5.1 and 5.2 respectively.

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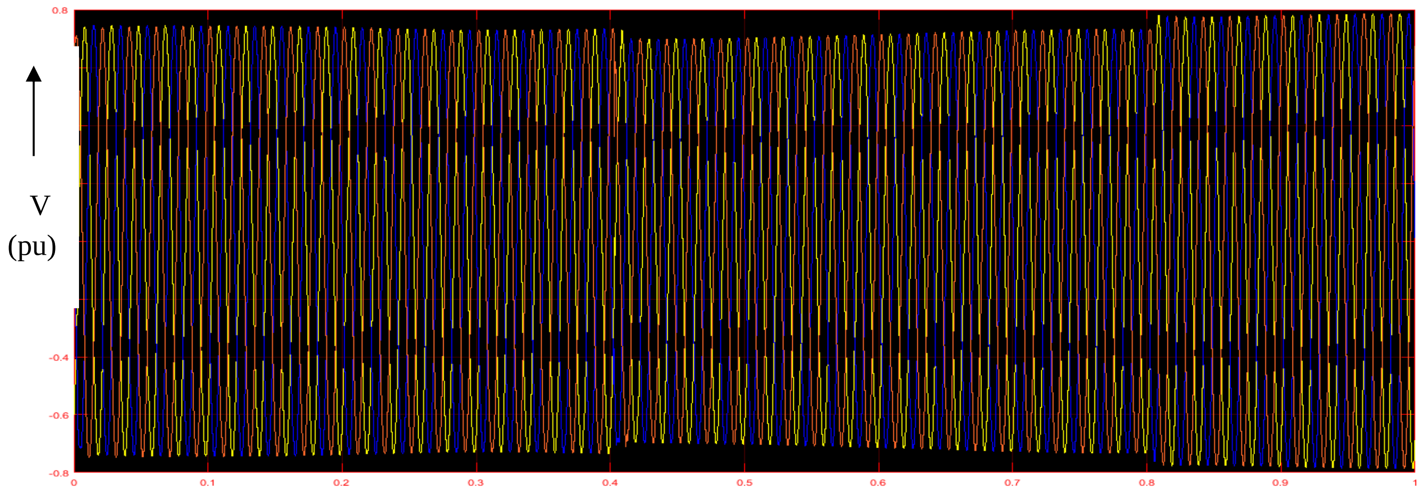

Fig.5.1: Voltage response for Yola bus at P_{max} wit Simulation Time (secs) **and with no device connected**

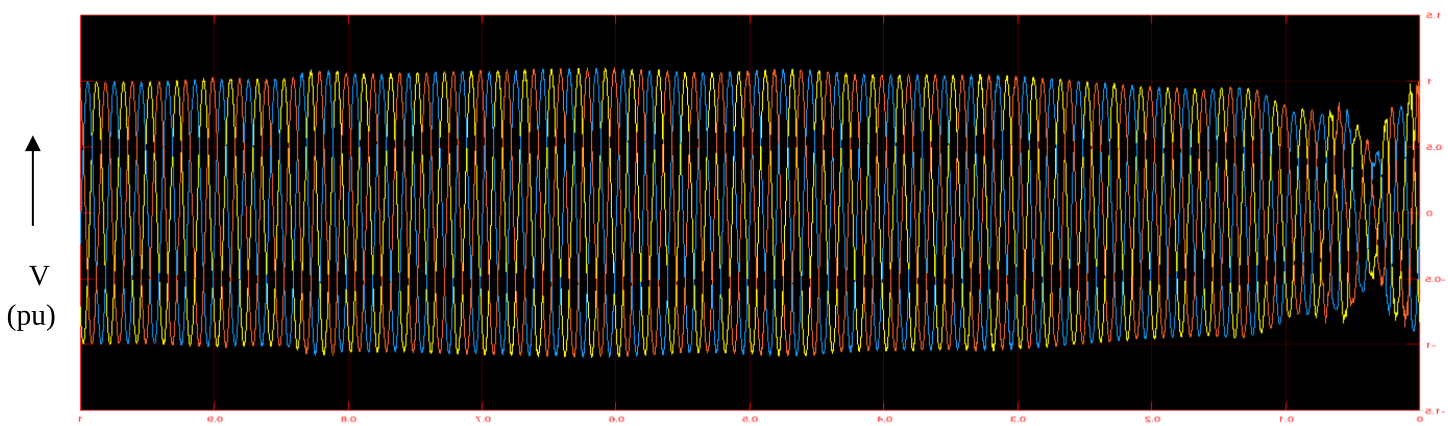

Fig 5.2: Voltage response for Yola bus at P_{max} with a sudden addition of large load and with HVDC-UPFC connected

Simulation Time (secs)

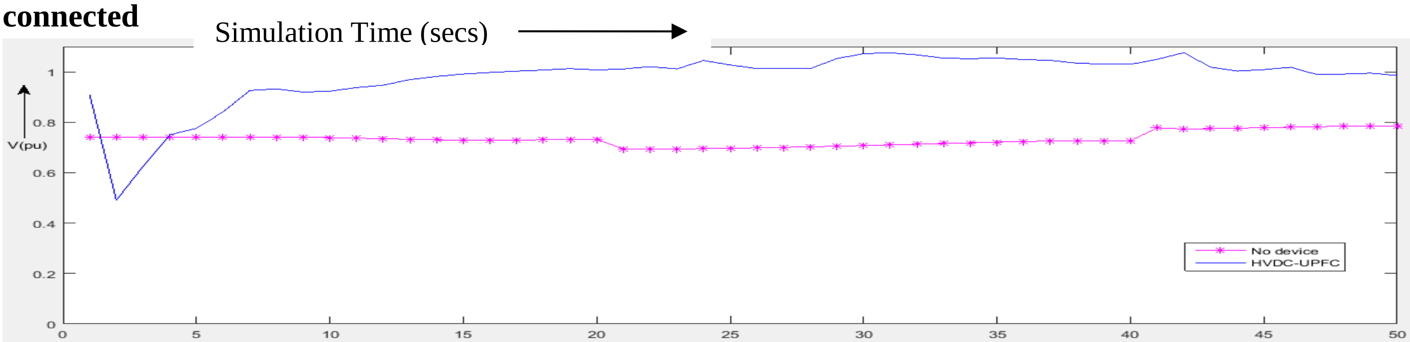

Fig 5.3: A graph of phase voltage profiles (with and without devices) against simulation time with a sudden addition of large load contingency imposed on the network.Fig 5.3 shows that the large load suddenly added to the network at the 20th second up to the 40th second reduced to the voltage profile to about 0.73pu. On the other hand, the connection of the HVDC-UPFC system to the network did not only prevent the voltage dip during period of load gain but also improved the voltage profile to approximately 1.05pu.

Table 5.1: Voltage profile of the weakest bus, Yola at critical during sudden gain of large load.

Contingency	No Device	HVDC-UPFC
Three Phase Fault	0.73	1.05

$$\text{VPSM} = \frac{1.05-0.73}{0.73} = 0.438 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ (5.1)$$

Table 5.1 and equation 5.1 show that the HVDC-UPFC system gave a 0.438 VPSM and a 43.8% enhancement in voltage stability during a contingency of gain in large load.

6 Conclusion

It can be concluded that relative to the network with no compensating device connected, HVDC-UPFC system peformed well in enhancing voltage stability of the test network during a contingency of gain of large load. Based on the results obtained in this research, it is recommended that UPFC and HVDC be installed to operate in parallel in our transmission networks near identified weakest buses as a way of enhancing the stability of the network so long as the network continue to suffer sudden change in loads, inadequate generating and transmitting, aged equipment, poor generating capacities and other external contingencies.

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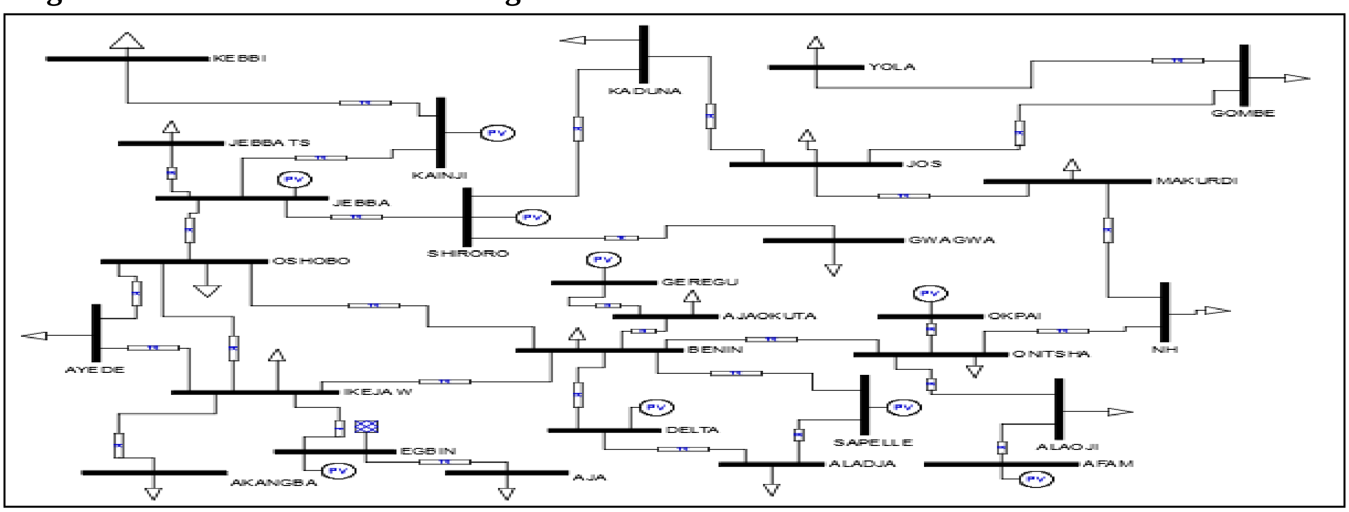
APPENDIX A

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



APPENDIX B

Equivalent network model showing Yola, Gombe, Jos and Kaduna buses a sudden addition of large load and with no device connected

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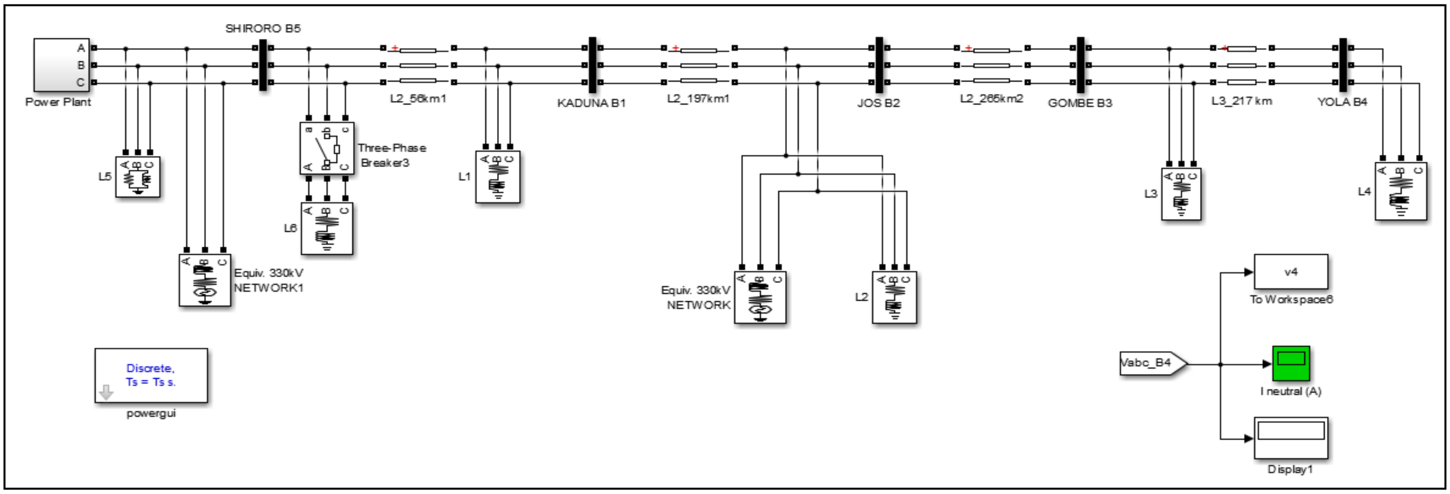

APPENDIX C

Equivalent network model showing Yola, Gombe, Jos and Kaduna buses a sudden addition of large load and with HVDC-UPFC connected