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Improving Power System Stability in A National Grid Using the Dynamic Voltage Restorer (DVR)

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ABSTRACT

Generation, transmission and distribution are the three subunits into which electric power grid is divided for efficient power supply. This paper proposes the method of power system stability in a national grid using Dynamic Voltage Restorer (DVR). DVR is a series custom connected power device meant to detect and compensate for sags in order to insulate loads from power reliability issues. They can be implemented at both low voltage (LV) and high voltage (HV) levels. Power system instability was established and its stabilization was demonstrated. The Nigerian 330KV, 30 bus system was used to demonstrate the DVR application. The characterized 330KV was made up of 6 generators, 24 loads, 30 buses and 31 transmission lines and used for the demonstration of the work. Using its Simulink model, the DVR was integrated into the Nigerian 330KV, 30 bus power system. This was simulated and results generated for analysis which showed stable power after the use of DVR. It was further discovered that there is need to optimize DVR operation using heuristic algorithms like particle swamp optimization (PSO), ant colony optimization (ACO) and simulated annealing (SA) for improved result.

Keywords: *Dynamic Voltage Restorer (DVR), Power Generation, Transmission and Distribution, Low Voltage, High Voltage, 330KV, 30 bus power system.*

Introduction

The electric power grid is divided into three subunits to ensure efficient power supply to the final consumer. These subunits are the generation, transmission and distribution subsystems. In accordance with appropriate induction laws such as Faraday's and Lenz laws of electromagnetic induction, electric power is generated through various natural resources such as water, wind, sun, coal and other fossil fuels. This generated power which typically lies in the range between 12KV to 25KV undergoes a step-up process through a transformer to a much higher voltage in the range of 110KV to almost 1000KV for further transmission over distant locations by the transmission stations and at much minimized losses. The distribution substations then use a step-down transformer to step the voltage down to a range of 12KV to 34.5KV for local distribution and finally permits the power to be used securely in homes, offices, factories and some very Light industries at voltages as low as 120V.

According to (Hadi, 2006), "power system stability is the ability of the power system to return to its normal operating conditions after a disturbance or perturbation". Put in a separate form, the tendency of a power system to initiate counter forces equivalent to or more superior than the disturbing forces to maintain balance is known as stability. Steady-state voltage stability or small disturbance voltage stability therefore refers to the capability of the electrical power system to keep up stable voltages when subjected to small perturbations. In view of this, power system stability is achieved only when the forces acting to keep the power system machines in synchronism with each other are large enough to overcome the disturbing forces. In order to meet up with the ever-increasing load demand for electricity in a power system, it is necessary to enhance the transmitted power either by installing fresh transmission lines or by improving the existing transmission lines by adding devices. The characterization of voltage sags is related with the magnitude of remaining voltage during sag and duration of sag. In practice the magnitude of the remaining voltage has more influence than the duration of sags on the system. One new approach is using the Dynamic Voltage Restorer (DVR) (voltage source converters connected in series between the supply system and the sensitive load). The DVR has recently been introduced to protect sensitive loads from voltage sags and other voltage disturbances; in addition to this it mitigates harmonics distortion. The DVR is specifically designed for large loads ranging from a few MVA up to 50 MVA or higher. The DVR can be implemented at both a low voltage (LV) level as well as, a high voltage (HV) level. The DVR is a series of connected custom power devices. Today, the dynamic voltage restorer is one of the most effective Power Quality devices in solving voltage sag problems.

Review of Related Works

The following reviews of related works are presented to buttress the points being established in this research.

Olaiba and Olulope (2019) in Voltasge stability in Nigerian Power Grid: A detailed literature review, presented critical review of the current national electricity grid in Nigeria. The maintenance of stability and limitations of transmission network as well as comparison of different options for overcoming transmission limitations were presented and analyzed. Previous literature was used to learn about renewable energy use and sources in Nigeria. Finally, the prospects of developing electricity grid in Nigeria in relation to identify challenges were highlighted. Possibility of generating various forms of energy from different sources was discovered. Common grid failure arising from system limitation of not employing the ideal, VAR controlling equipment, capable of producing cascaded power outages was a major shortfall. The paper opined that the generation of wind energy should be looked into with a view to incorporating it into the national grid.

Reza et al (2017) carried a work on Control Strategy for Enhancing Frequency Stability by DFIG in a Power System with High Percentage of Wind Power Generation. Fuzzy logic controller (FLC) with emotional based intelligent controller technique was used. The paper presented a model of DFIGs for dynamic studies in frequency stability analysis. A model of a coordinated control strategy to regulated active power command set point (PCMD) for individual WTGs in a wind farm (WF) and a control strategy to regulate wind power output of DFIG upon operator's request was also presented. Simulations of the modeled DFIG and WTGs were performed to validate the effectiveness of the research results. There is a need to further research into the implementation of the scheme in utility power industry where power distribution stability is desirable.

El-Dabh et al (2015) also did another work on Frequency Stability Enhancement of DG Based Power Systems Using Model Controller. VSG controller technique with synchronous references frame, phases locked loop (SRFP-PLL) was the research technique. The researchers presented three cases and investigated the effects of VSG solution towards grid frequency stabilization. Case 1 involved 2N0. SGs connected to a grid with a VSG connected to the same grid. Case 2 involved replacing one of the SGs with a VSG and connected to a grid. Case 3 involved connecting a 100kW

VSG with a SG of same capacity as VSG. All the simulation results obtained validated the feasibility of the control strategy. The effectiveness of VSG in grid frequency stability was not technically in doubt. But the paper did not reveal the cost implication of this scheme and the limitation of grid capacity whose frequency is to be controlled.

Methodology

The crux of this research is to establish the existence of instability in power systems and to subsequently describe how power system stability can be improved upon by using the dynamic voltage restorer (DVR) in minimizing voltage sags and swells in any given power system. The Nigerian 330KV 30 bus power system was test bed used in carrying out this research. The Nigerian 330KV 30 bus power system will be described and modeled in Simulink and simulated. Voltage measurement (load flow) would be carried out in its conventional Simulink model so as to determine the degree of instability present in the power system. Thereafter, the dynamic voltage restorer (DVR) and its control circuit would also be modeled in Simulink to be used in controlling the flow of power as well as swells/sags in voltages in the unstable Nigerian 330KV 30 bus power system. Finally, the DVR model would be incorporated into the unstable Nigerian 330KV 30 bus power systems and simulation would again be performed. The load flow results of the Nigerian 330KV 30 bus power systems before and after the applying DVR will then be used for evaluation and justification of the research. The algorithm used in this research is as follows.

Algorithm of the Research

1. Model Nigerian 330 KV 30 bus Power Supply in Simulink.
2. Enter input values from characterization.
3. Simulate to perform load flow measurements.
4. Model DVR control circuit in Simulink.
5. Simulate to confirm working circuit.
6. Power System Stability characterized?
7. Yes. Go to 9.
8. No. Go to 1.
9. Install DVR at different sections of the Nigerian 330KV 30 bus system.
10. Simulate new system with installed DVR.
11. Compare with load flow results in 3.
12. Are results with DVR better than results without DVR?
13. Yes. Go to 15.
14. No. Go to 4.
15. Proved power system stability?
16. Yes. Go to 18.
17. No. Go to 1.
18. End.

The Nigerian 330 KV 30 bus power system was then characterized. It is made up of 6 generators, 24 loads, 30 buses and 31 transmission lines. The generator buses consist of the following:

1. Egbin GS (Slack bus)

2. Afam (Bus 5)
3. Sapele (Bus 1)
4. Jebba GS (Bus 2)
5. Kainji (Bus 6)
6. Shiroro GS (Bus 3)

The load buses comprise the following:

1. Birnin Kebbi (Bus 11)
2. Kaduna (Bus 17)
3. Kano (Bus 18)
4. Maidugri (Bus 28)
5. Shiroro TS (Bus 9)
6. Sokoto (Bus 27)
7. Jos (Bus 19)
8. Gombe (Bus 20)
9. Jebba (Bus 8)
10. Abuja (Bus 30)
11. Aba (Bus 24)
12. Aladja (Bus 25)
13. Benin (Bus 21)
14. Delta (Bus 7)
15. Ikeja west (Bus 14)
16. Makurdi (Bus 29)
17. Onitsha (Bus 23)
18. Oshogbo (Bus 12)
19. Aja (Bus 16)
20. Ajaokuta (Bus 22)
21. Akangba (Bus 15)
22. Egbin TS (Bus 10)
23. Enugu (Bus 26)
24. Ibadan (Bus 13)

The single line diagram of the Nigerian 330KV 30 bus power system is shown in Figure 3.1. A model of the single line power system diagram is also shown in Figure 3.2 using the power system analysis toolbox (PSAT) and also modeled in Simulink to enable the load flow analysis (simulation and voltage measurement) to be achieved using it.

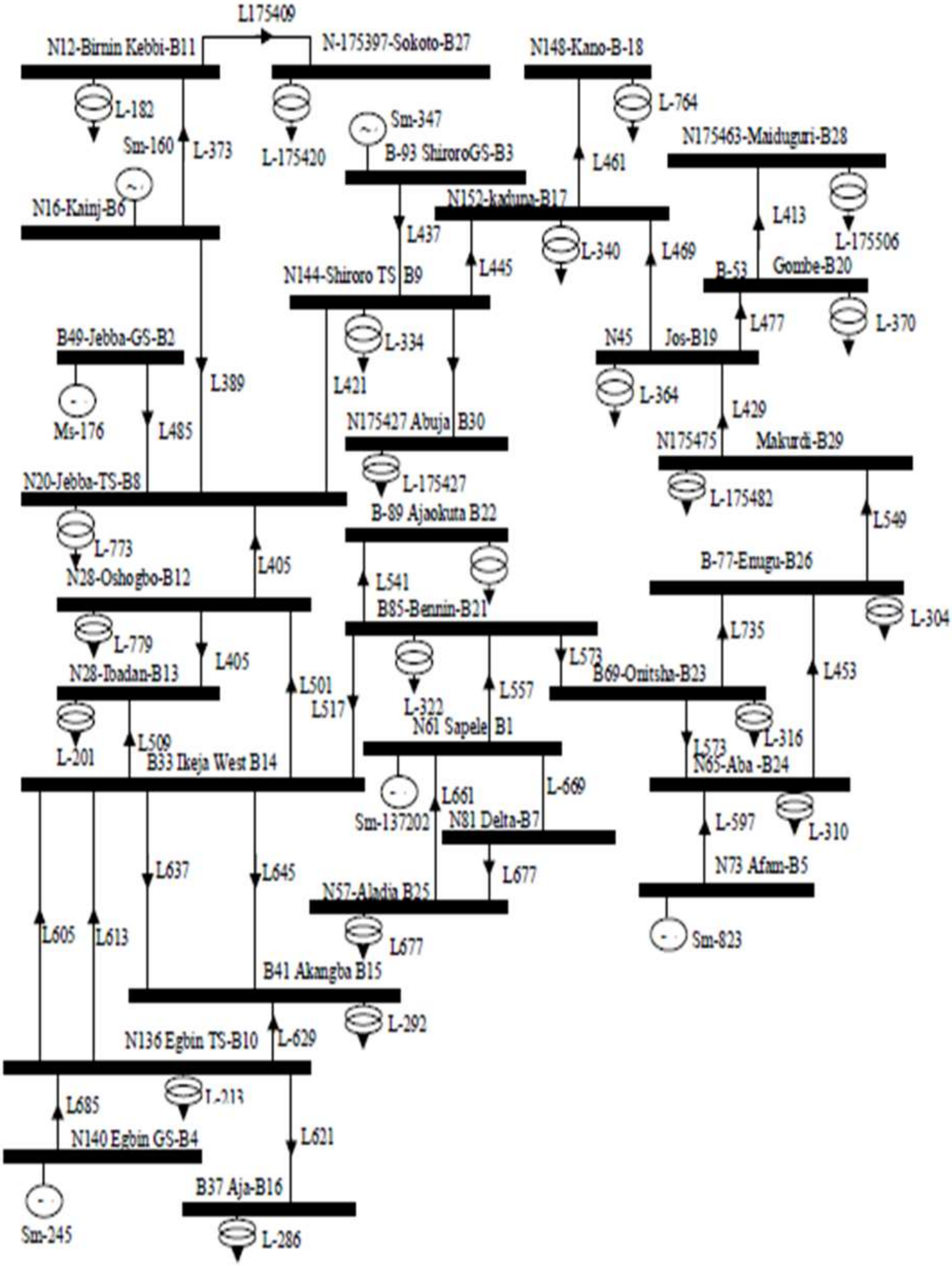

Fig 3.1: Single Line Diagram of the Nigerian 330KV 30 bus Power system

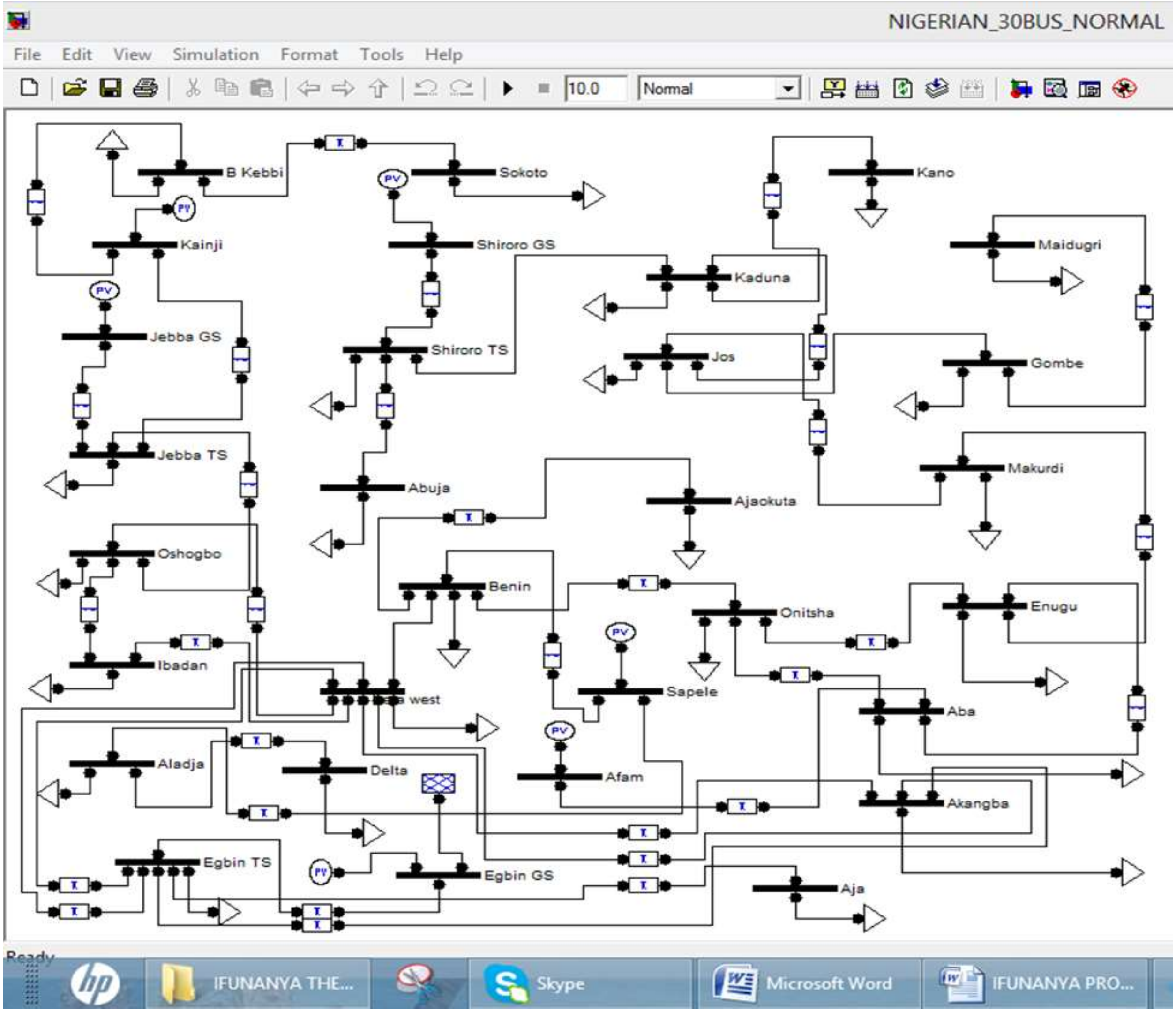

Fig 3.2: PSAT Model of the Nigerian 330KV 30 Bus power System

The PSAT model of the Nigerian 330KV 30 bus power system is shown in Figure 3.2. Using the PV and slack bus blocks the generator buses were modeled while the load block was used to model buses. Modeling the transmission lines was achieved using the three-phase pi model transmission line. The Simulink model for the Nigerian 330KV 30 bus power system is presented in Figure 3.3.

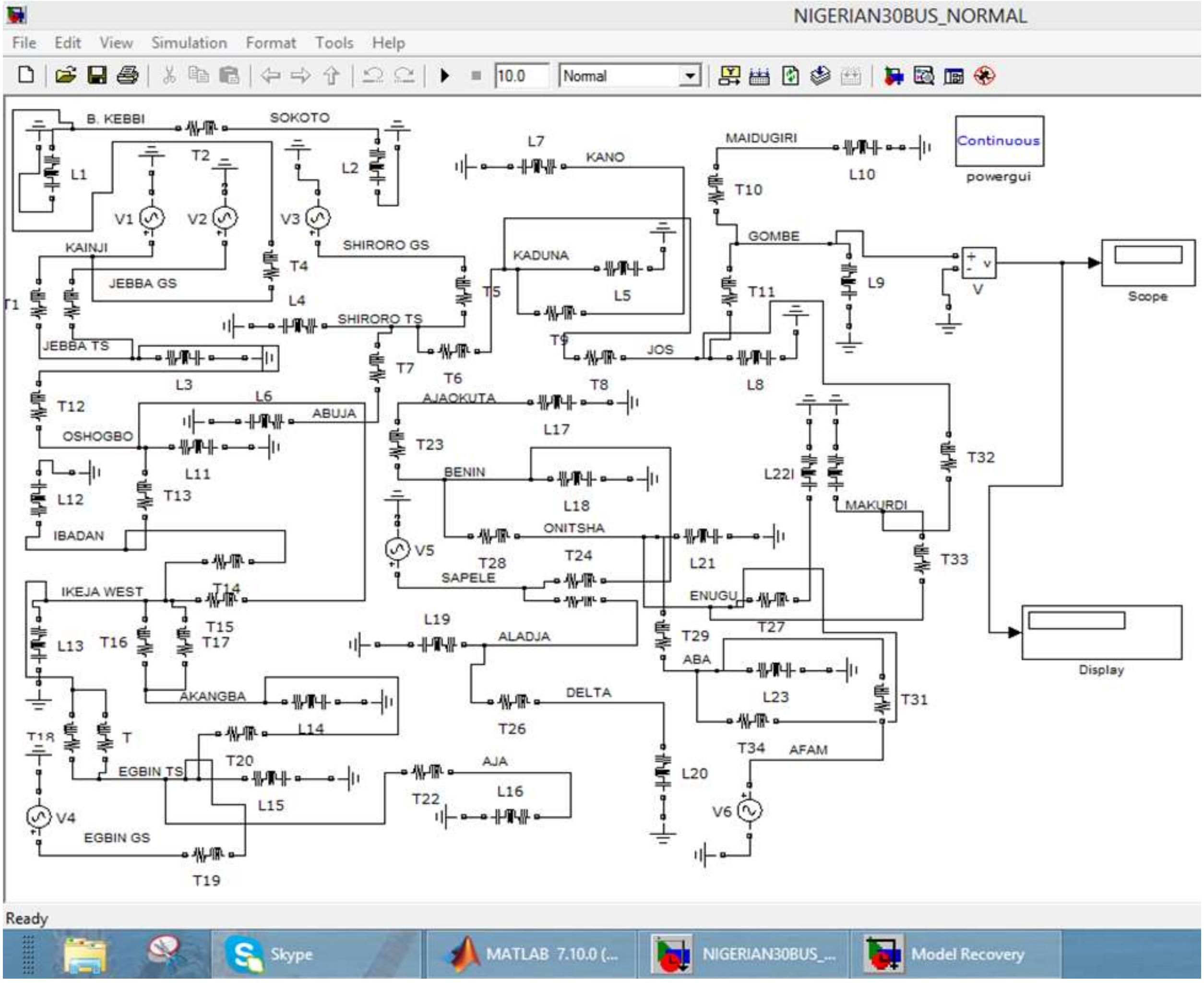

Fig 3.3: Simulink Model of the Nigerian 330KV 30 Bus Power System

Having designed and presented all the necessary models relating to the Nigerian 330KV 30 bus power system, those relating to the DVR which are used in this work to improve power system stability are also presented. The dynamic voltage restorers (DVRs) also regarded as the pulse width modulated (PWM) regulators are series of controllers for controlling the fundamental voltage of a power system. In this work, relevant controllers were used. In figure 3.4, the circuit diagram of a system with series controller is presented as a way of presenting power system stability control measures.

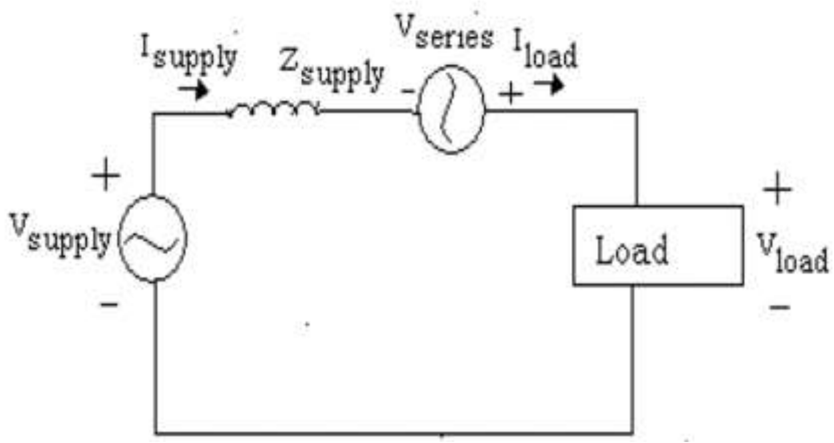

Fig 3.4: Circuit diagram of a system with series controller

In Figure 3.4, the protected load is connected in series with the series voltage controller, a connection normally made through a transformer. The resulting voltage at the load bus bars is equal to the combination of the grid voltage and the voltage introduced by the DVR. The extent and depth of the voltage sag that can be compensated by the DVR is often limited. It is thus required to select the right size in order to achieve the anticipated protection.

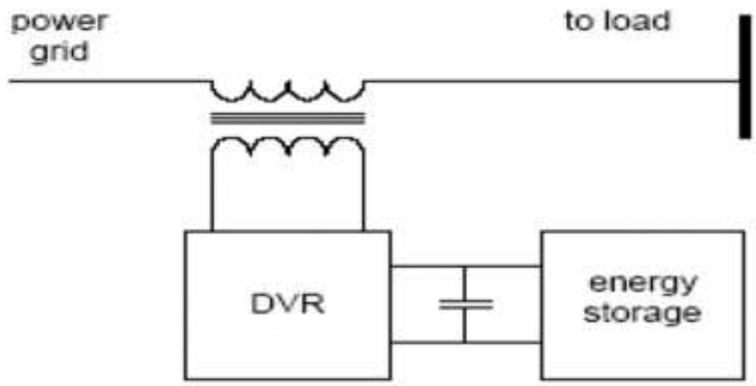

Figure 3.5: Configuration of a DVR

Also, a configuration of DVR is shown in Figure 3.5 as a power system stability measure. Given a series connection of the DVR with the load in the Nigerian 330KV 30 bus power system lines, the following system arrangement in Figure 3.6 is in use.

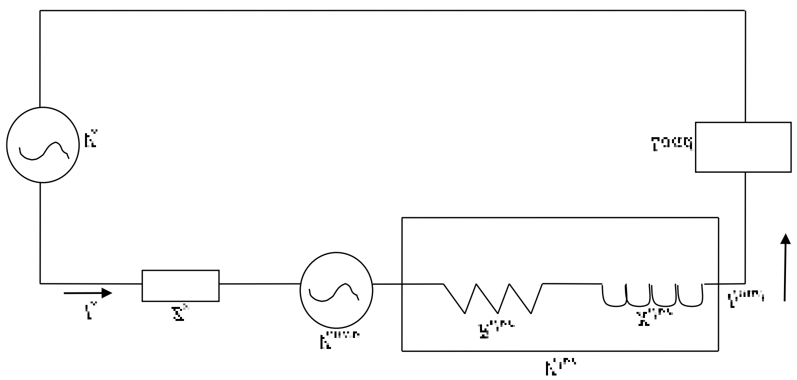

Figure 3.6: Equivalent circuit of a power system with DVR

The following mathematical relationships relating to the circuit arrangement of Figure 3.6 are derived and presented.

Given thatV_conv is the ideal voltage source with inserted restive and reactive load and impedance (R_dvr and X_dvr) respectively, and represents the losses in the DVR. The magnitude of the inserted impedance is closely related to the DVR voltage rating (V_dvr) and the DVR power rating (S_dvr) from the following equations

$$X_{dvr} = \left(\frac{V_{dvr}^2}{S_{dvr}}\right) \times V_{dvr,X} \quad \ldots 3.1$$

$$R_{dvr} = \left(\frac{V_{dvr}^2}{S_{dvr}}\right) \times V_{dvr,R} \quad \ldots 3.2$$

$$Z_{dvr} = \left(\frac{V_{dvr}^2}{S_{dvr}}\right) \times V_{dvr,Z} \quad \ldots 3.3$$

Therefore

$$V_{dvr,Z} = V_{dvr,R} + jV_{dvr,X} \quad \ldots 3.4$$

Any DVR that has a high injection capability (ie HighV_dvr) and the ability to protect a small load (ie low S_dvr) will have large equivalent DVR impedance (ie largeZ_dvr).

From the Thevinin model of the DVR, the Thevinin impedance is the resultant of fixed resistance which is equivalent to the losses in the DVR, and the fixed reactance which is equivalent to the reactive elements of the DVR. The voltage injection capability of the DVR can therefore be given by

$$V_{dvr}\% = \left(\frac{V_{dvr}}{V_{supply,rated}}\right) \times 100 \quad \ldots 3.5$$

The Voltage rating and current rating of a DVR affects its performance. The DVR voltage can be expressed in terms of its load current and the thevinin voltage as

$$V_{dvr} = V_L + Z_{th}I_L - V_{th} \quad \ldots 3.6$$

The load current I_L is given by

$$I_L = \frac{P + jQ_L}{V_L} \quad \ldots 3.7$$

The load power factor angle is given by

$$\Theta = \tan^{-1}\left(\frac{P_L}{Q_L}\right) \quad \ldots 3.8$$

Assuming the thevinin impedance is very less (ie $Z_{th} \ll 1$), the injected voltage by the DVR can be written as

$$V_{dvr} = V_L - V_{th} = (1 - K)V_L \quad \ldots 3.9$$

$$K = \frac{V_{th}}{V_L} \quad \ldots 3.10$$

The apparent power that is required by the DVR (S_{dvr}) is calculated in terms of the apparent load power (S_L).

$$S_{dvr} = S_{L(1-K)} \qquad ...3.11$$

$$S_{dvr} = V_{dvr}\, I_L^* \qquad ...3.12$$

By separating the apparent load power into its real and imaginary components, the active and reactive power can be calculated as follows:

$$Q_{dvr} = S_L \sin(\Theta_L) - K sin(\Theta_S) \qquad ...3.13$$

$$P_{dvr} = S_L \cos(\Theta_L) - K cos(\Theta_S) \qquad ...3.14$$

Where $\cos(\Theta_L)$ and $cos(\Theta_S)$represents the load power factor and the source power factor.

Therefore,

$$P_{dvr} = P_L\left(1 - \left(\frac{V_{th}\cos(\Theta_L + \Phi)}{\cos(\Phi_L)}\right)\right) \qquad ...3.15$$

Results and Discussion

Figure 1a shows the XRD pattern of the untreated alloy, while Figures 1b-1e display the XRD patterns of the heat-treated samples. From the XRD spectrum of the alloy, it is observed clearly that there is presence of Ni, Fe (Awaruite), AL0.3Fe3 Si0.7 (Aluminum iron Silicon), and Cr7C3 (carbon Chromium) phases. After heat treatment it is observed that new phases appeared such as: FeSi (Fersilicite, syn [NR]), Managnese Carbide, Chromium Iron Carbide, Manganese Silicon Carbide. The presence of (Ni, Fe) (Awaruite) phase is common to all the samples; this expected because the specimen is a Ni-Fe base super-alloy. By comparing the XRD of the control (Figure 1a) with the heat-treated samples (Figures 1b- 1c), one can observe that there is a great change in the spectrum which resulted in more diffraction peaks, and a larger quantity of hard carbides with smaller inter-particle distance. In the heat-treated samples, it is clear that the various phases formed after the heat treatment depends on the heat treatment condition as shown in Table 2.

From equation 3.15, the load voltage of the test power system can be assumed to be 0.95 pu.

A Simulink model of the DVR is shown in Figure 3.7. The parameters to be imputed into the PSAT model of the DVR will be derived from these equations. Four voltage measurement blocks were connected to a NAND gate through two relational operators which forms the comparator for the control circuit of the DVR. Two data conversion blocks and one pulse generator were also used in modeling the control circuit. The DVR was modeled using four metal oxide semi-conductor field effect transistors (MOSFETs), one DC voltage source and one single phase transformer.V1 is the power system voltage while V1ref and V2ref are the reference voltage of the comparator.V1ref is set as 313500V (ie 0.95pu) and V2ref is set as 346500V (ie 1.05pu).Under normal operating conditions, the voltage across the transmission lines are within the range of 0.95pu to 1.05pu and the DVR does not operate.

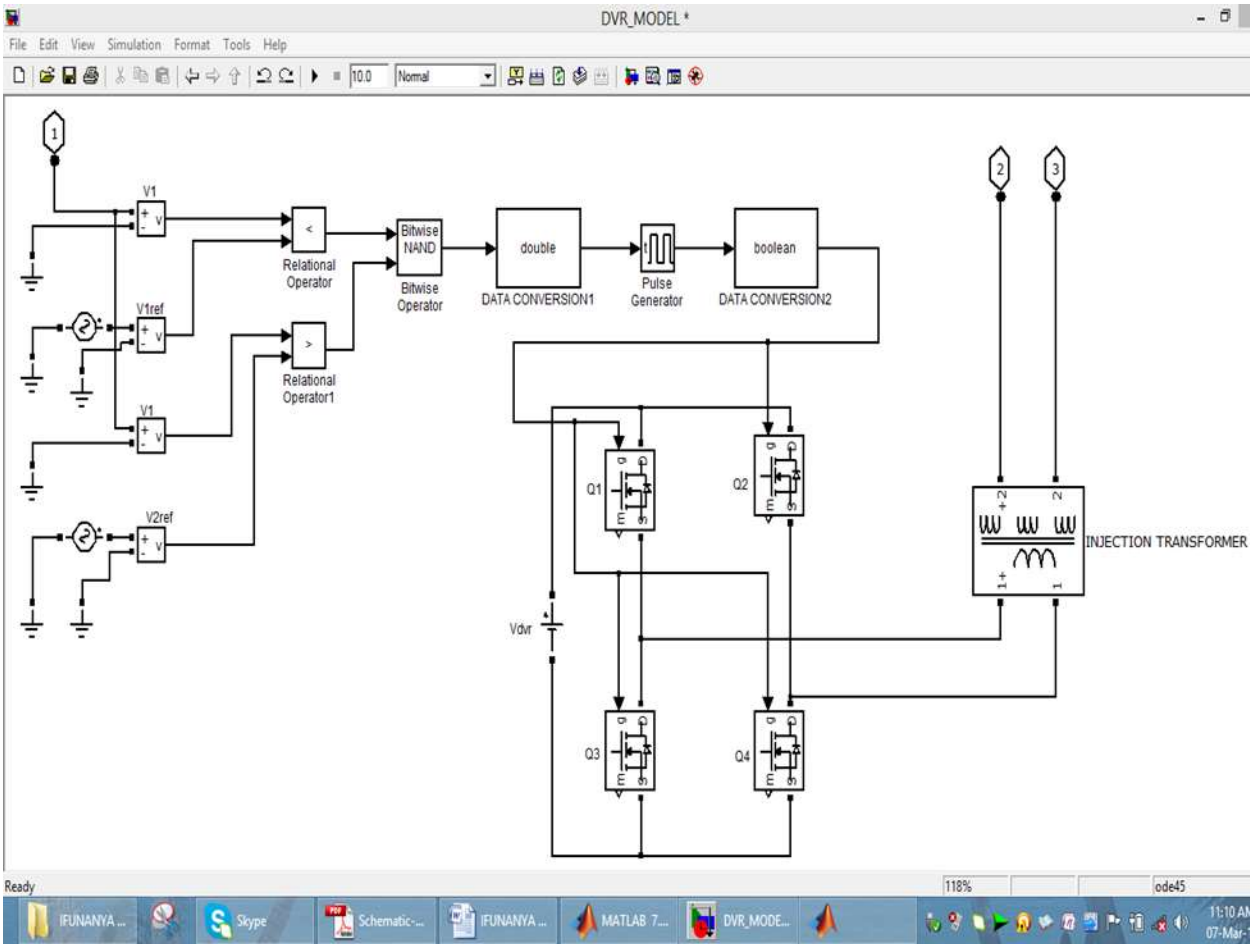

Figure 3.7: Simulink Model of the DVR

However, when a voltage sag or swell occurs in the power system, the first relational operator which is set in less than mode compares V1 and V1ref to see if VI falls below 0.95pu and then sends its output to the NAND operator. On the other hand, the second relational operator which is set in greater than mode compares V1 and V2ref to see if V1 is greater than V2ref and also sends its output to the NAND operator. The NAND operator ensures that the signals from both relational operators are not combined together and then sends its output to the first data conversion block which converts its output to the double data type so that the pulse generator can understand it.

Simulation, Results and Discussion

The DVR will be integrated into the Simulink model of the Nigerian 330KV 30 bus power system and the simulation and measurement will again be carried out. Figures 4.1, 4.2 and 4.3 show three DVRs connected across Benin, Kano and Ikeja west 330KV transmission lines. The DVR blocks in the Simulink model of the Nigerian 330KV 30 bus power system represents a subsystem of the DVR Simulink model. They are labeled according to the bus to which they are connected. The DVR subsystem also contains the control circuit of the DVR. The load flow of the Nigerian 330KV 30 bus power system is performed with the DVR attached thus making sure that the DVR is used to vary the load flow parameters of the system. The results indicate that the integration of the DVR into the Simulink model of the Nigerian 30 bus power system improved the bus voltage profile by compensating for the voltage sags and swells in the system during contingency events.

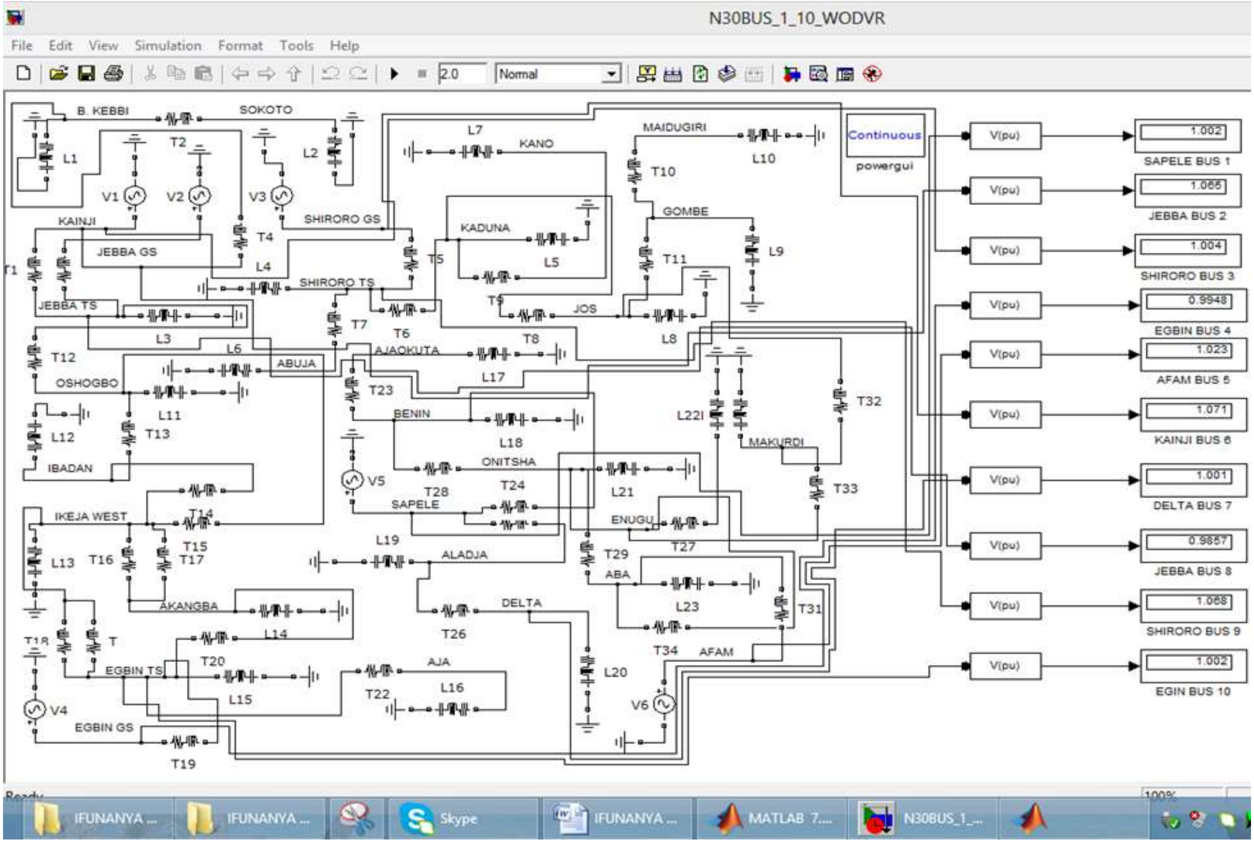

Figure 4.1: Nigerian 30 bus power system without DVR and Measurement at Buses (1-10)

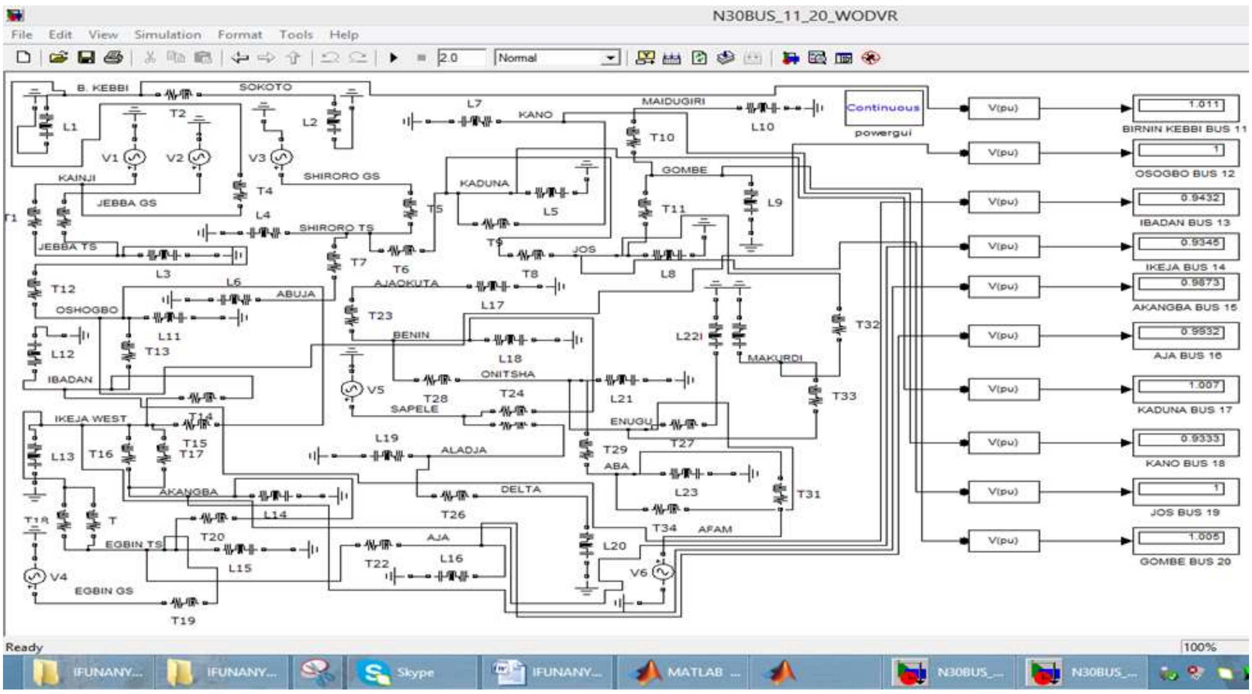

Figure 4.2: Nigerian 30 bus power system without DVR and Measurement at Buses (11-20)

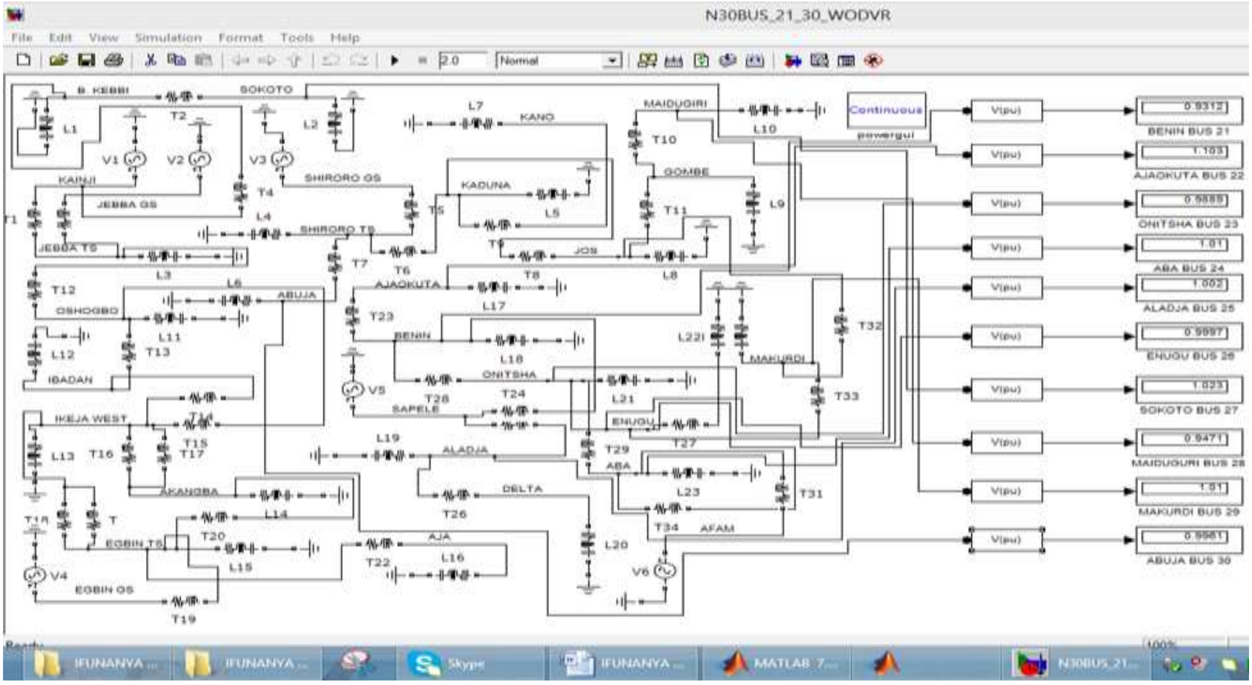

Figure 4.3: Nigerian 30 bus power system without DVR and Measurement at Buses (20-30)

Table 4.1: Summary of Simulation results of the Nigerian 330KV 30 bus power system without DVR

Bus no	Bus Name	Type of bus	Voltage (pu)	Voltage (KV)
1	Sapele	PG	1.002	330.66
2	Jebba GS	PG	1.065	351.45
3	Shiroro GS	PG	1.004	331.32
4	Egbin	PG	0.9948	328.284
5	Afam	PG	1.023	337.59
6	Kainji	PG	1.071	353.43
7	Delta	PG	1.001	330.33
8	Jebba TS	PQ	0.9857	325.281
9	Shiroro TS	PQ	1.068	352.44
10	Egbin	PQ	1.002	330.66
11	Birnin Kebbi	PQ	1.011	333.63
12	Osogbo	PQ	1	330
13	Ibadan	PQ	0.9432	311.256
14	Ikeja West	PQ	0.9345	308.385

15	**Akangba**	**PQ**	**0.9873**	**325.809**
16	**Aja**	**PQ**	**0.9932**	**327.756**
17	**Kaduna**	**PQ**	**1.007**	**332.31**
18	**Kano**	**PQ**	**0.9333**	**307.989**
19	**Jos**	**PQ**	**1**	**330**
20	**Gombe**	**PQ**	**1.005**	**331.65**
21	**Benin**	**PQ**	**0.9312**	**307.216**
22	**Ajaokuta**	**PQ**	**1.042**	**343.86**
23	**Onitsha**	**PQ**	**0.9889**	**326.337**
24	**Aba**	**PQ**	**1.01**	**333.3**
25	**Aladja**	**PQ**	**1.002**	**330.66**
26	**Enugu**	**PQ**	**0.9997**	**329.901**
27	**Sokoto**	**PQ**	**1.023**	**337.59**
28	**Maiduguri**	**PQ**	**0.9471**	**312.543**
29	**Makurdi**	**PQ**	**1.01**	**333.3**
30	**Abuja**	**PQ**	**0.9961**	**328.713**

As can be seen from Figures 4.1, 4.2, 4.3 and Table 4.1, two generator (PV) buses were unstable while five load (PQ) buses were unstable thereby making a total of seven unstable buses and twenty-three stable buses. The unstable buses were so because they either exceeded or did not reach the minimum permissible voltage for stability which is 313.5KV-346.5KV (ie 0.95pu-1.05pu). These unstable buses are therefore identified below:

1. Jebba GS- 1.065pu, 351.46KV
2. Kainji- 1.071pu, 353.43KV
3. Shiroro- 1.068pu, 352.44KV
4. Ibadan- 0.9432pu, 311.256KV
5. Ikeja west- 0.9345pu, 308.385KV
6. Kano- 0.9333pu, 307.989KV
7. Benin- 0.9312pu, 307.216KV

According to Yangzhou's definition of power system stability, if you have one thousand (1000) buses in a power system and nine hundred and ninety-nine (999) buses is stable while one (1) bus is unstable, that means that the whole power system is unstable. So, this means that the Nigerian 330KV 30 bus power system is unstable.

Simulation results of the Simulink models of Figures 4.1, 4.2 and 4.3 are shown in Figures 4.4, 4.5 and 4.6.

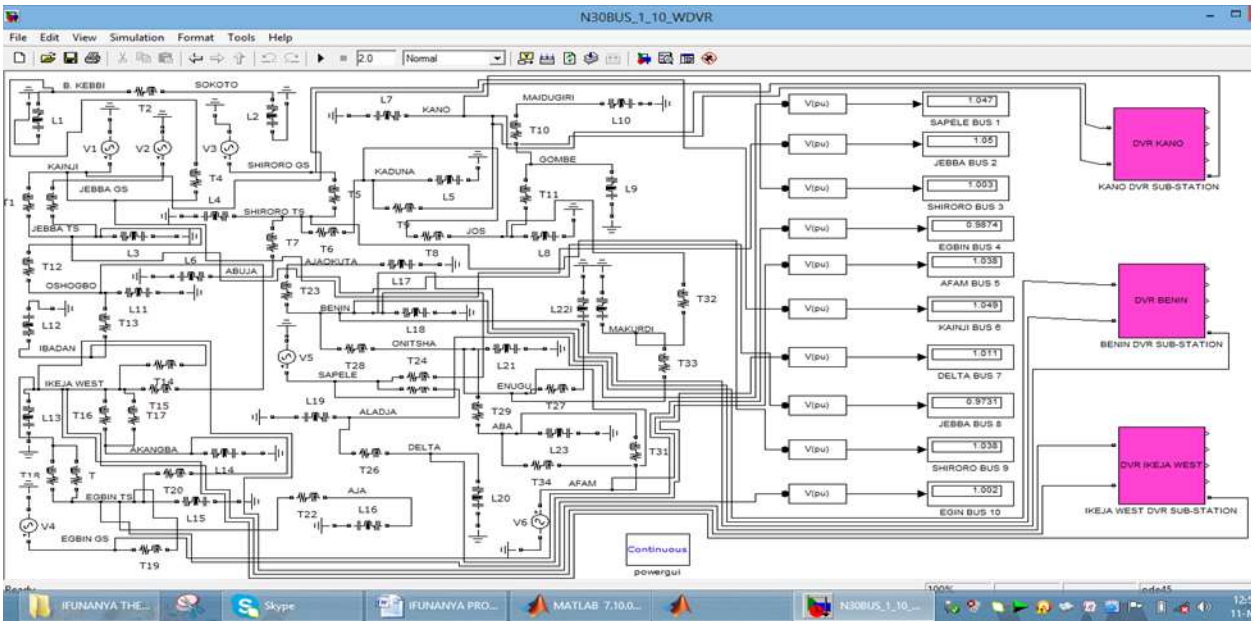

Fig 4.4: Simulation and Voltage Measurement of the Nigerian 30 bus Power System with DVR (Buses 1-10)

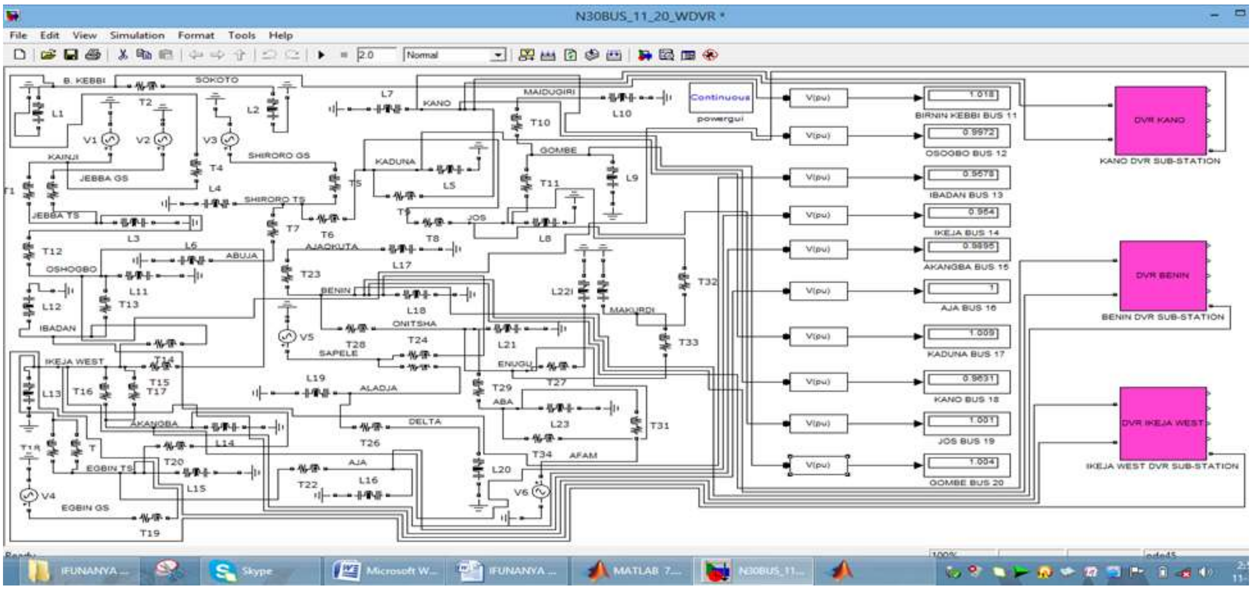

Figure 4.5: Simulation and Voltage Measurement of the Nigerian 30 bus Power System with DVR (Buses 11-20)

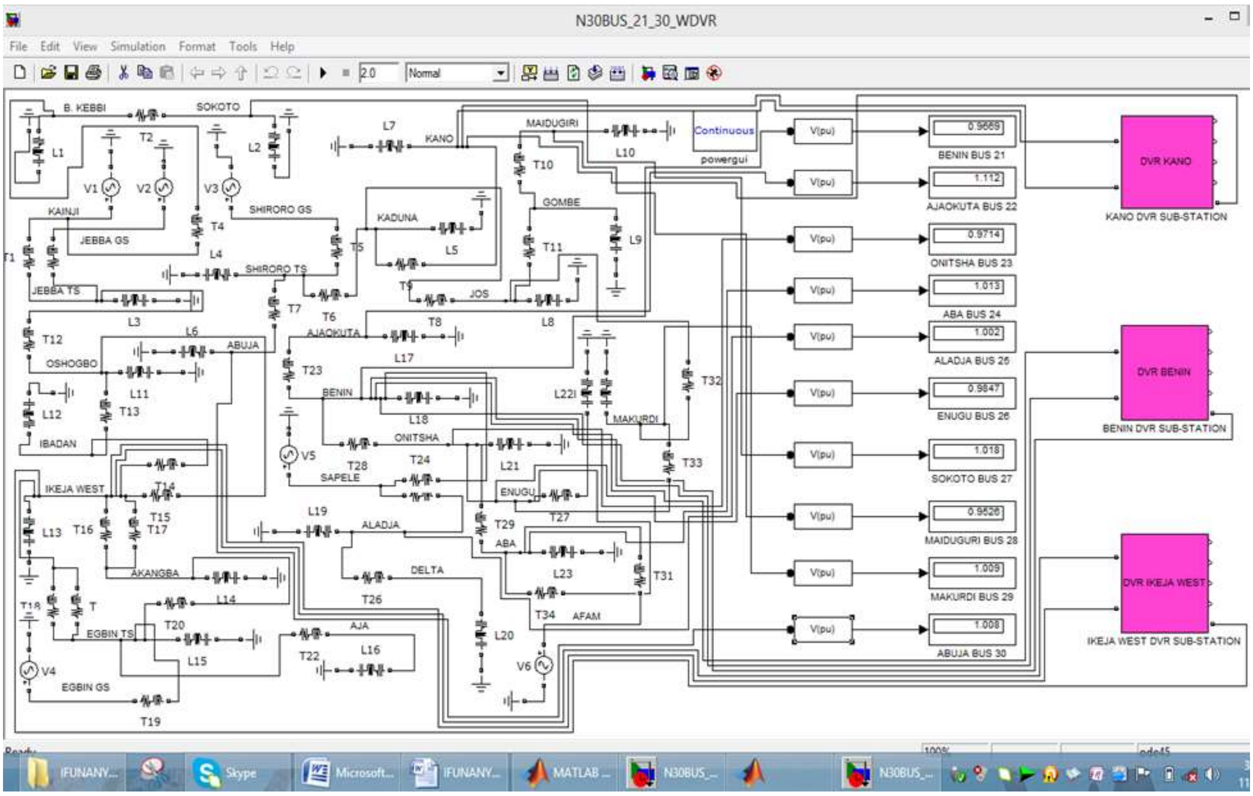

Figure 4.6: Simulation and Voltage Measurement of the Nigerian 30 bus Power System with DVR (Buses 21-30)

Table 4.2: Summary of Simulation results of the Nigerian 330KV 30 bus power system with DVR

Bus no	Bus Name	Type of bus	Voltage (pu)	Voltage (KV)
1	Sapele	PG	1.047	345.51
2	Jebba GS	PG	1.05	346.5
3	Shiroro GS	PG	1.003	330.99
4	Egbin	PG	0.9874	325.842
5	Afam	PG	1.038	342.54
6	Kainji	PG	1.049	346.17
7	Delta	PG	1.011	333.63
8	Jebba TS	PQ	0.9731	321.123
9	Shiroro TS	PQ	1.038	342.54
10	Egbin	PQ	1.002	330.66
11	Birnin Kebbi	PQ	1.018	335.94
12	Osogbo	PQ	0.9972	329.076

13	**Ibadan**	**PQ**	**0.9578**	**316.074**
14	**Ikeja West**	**PQ**	**0.954**	**314.82**
15	**Akangba**	**PQ**	**0.9895**	**326.535**
16	**Aja**	**PQ**	**1**	**330**
17	**Kaduna**	**PQ**	**1.009**	**332.97**
18	**Kano**	**PQ**	**0.9631**	**317.823**
19	**Jos**	**PQ**	**1.001**	**330.33**
20	**Gombe**	**PQ**	**1.004**	**331.32**
21	**Benin**	**PQ**	**0.9669**	**319.077**
22	**Ajaokuta**	**PQ**	**1.026**	**338.58**
23	**Onitsha**	**PQ**	**0.9714**	**320.526**
24	**Aba**	**PQ**	**1.013**	**334.29**
25	**Aladja**	**PQ**	**1.002**	**330.66**
26	**Enugu**	**PQ**	**0.9847**	**324.951**
27	**Sokoto**	**PQ**	**1.018**	**335.94**
28	**Maiduguri**	**PQ**	**0.9526**	**314.358**
29	**Makurdi**	**PQ**	**1.009**	**332.97**
30	**Abuja**	**PQ**	**1.008**	**332.64**

As can be seen from Figures 4.4 to 4.6 and Table 4.2, all the buses in the power system are now stable as they all met the criteria for voltage stability which is 313.5KV-346.5KV (ie 0.95pu-1.05pu). This is as a result of the injection of voltage during voltage sags or swells by the dynamic voltage restorer (DVR). Those buses that were unstable before applying the DVR but are now stable after applying the DVR are listed below alongside their measured voltages in per unit and kilo volt.

1. Jebba GS- 1.05pu, 346.5KV
2. Kainji- 1.049pu, 346.17KV
3. Shiroro- 1.038pu, 342.54KV
4. Ibadan- 0.9578pu, 316.074KV
5. Ikeja west- 0.954pu, 314.82KV
6. Kano- 0.9631pu, 317.823KV
7. Benin- 0.9669pu, 319.077KV

Discussion

Stability analyses are classified with regards to the order and magnitude of the resulting disturbance. As has been established, there are steady-state stability, transient stability, and dynamic stability. In this presentation, DVR was used to stabilize the Nigerian 330KV 30 bus power system in all stability conditions because power system transits to these three stability states depending on the condition at any given time. Thus, these states were taken into consideration in the stability measures carried out in this work.

The dynamic mode of power system stability is, however, always considered due to its frequency in power system operation. Results generated in this work showed that appreciable stability has been achieved in the Nigerian 330KV 30 bus power system using Dynamic Voltage Restorer, DVR. A comparison of data contained in Tables 4.1 and 4.2 is used to express this phenomenon. While Table 4.1 contains pu and voltage values simulation results without DVR, Table 4.2 contains pu and voltage values simulation results with DVR. Data presented in both tables differ showing that those with DVR shown in Table 4.2 are more stable than the data of Table 4.1 without DVR. This shows that using DVR, stability conditions of power systems can be improved as required in this work.

Conclusion

This work investigated how power system stability can be improved upon using the dynamic voltage restorer (DVR). Using Simulink, the power system under study was modeled and simulated to determine the conventional power system stability. This led to the discovery of the unstable buses. Similarly, the DVR was also modeled in Simulink after which it was integrated into the unstable power system. Subsequent simulation showed that the unstable buses had stabilized thus showing how good the DVR has been in improving power system stability.

Considering the foregoing results, the following conditions have been established. In any power system, voltage drops mostly occur in the buses that have the largest loads connected to them. However, for any power system to be declared stable, all buses in the power system must meet the minimum and maximum permissible parameters for stability. When a disturbance occurs in a power system, the voltage drops across some of the buses in the power system as well. The dynamic voltage restorer is not only capable of improving the steady state stability of a power system but also capable of improving its transient stability. It is recommended that the operation of the DVR in the power systems should be optimized using heuristic algorithms like the particle swarm optimization (PSO), the ant colony optimization (ACO) and simulated annealing (SA) for an improved result. Similarly, complex and large power systems should be modeled using software like the power system analysis tool box (PSAT), PSCAD, LT-SPICE, and NEPLAN for better and more reliable results.

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