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VOLTAGE STABILITY IN NIGERIA 330KV INTEGRATED 52 BUS POWER NETWORK USING PATTERN RECOGNITION TECHNIQUES: A RECURSIVE APPROACH

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KEYWORDS: Voltage Instability and Stability, PSSE, 330kV Integrated 52 bus Power System, RLSC, and CART.

ABSTRACT
Detecting the voltage instability in advance enables remedial actions and preventive measures to cushion the effect of the oncoming voltage collapse phenomenon in power systems. This was achieved by implementing Pattern Recognition Techniques (PRTs) in conjunction with Power System Simulator for Engineering (PSSE) program. It was then deployed in Nigeria 330KV Integrated 52 bus power system to actualize Regularized Least Squares Classification (RLSC) and Classification and Regression Trees (CART) heuristic methods. The methods were deployed for separating voltage stability and unstable cases that resulted under system contingencies and fault conditions. Dynamic simulation, system voltage stability and unstable/instability cases results, and the channel outputs of these voltage cases against time were realized.

INTRODUCTION
Electrical energy is an essential ingredient for the industrial and all-round development of any country. The quality of life in any country is highly dependent on a reliable electricity supply. The frequent system collapse in the Nigerian power sector has severally plunged the nation into darkness due to system instability in the Nigeria electric power system. The epileptic nature of the supply has resulted to slow economic growth and dissatisfaction among the citizenry [1, 2, 3].

To assist in overcoming the instability problems, analysis of the Nigerian electric power system becomes necessary. Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [4]. The stability of a particular generator or a group of generators is of interest. A remote generator may lose synchronism without causing cascading instability of the whole system. Similarly, stability of particular loads or load areas are also of interest [4].

Voltage stability is the ability of the power system to maintain steady acceptable voltages at all the buses in the system under normal operating conditions and after being subjected to a disturbance [5]. Voltage instability occurs when a disturbance, increase in load demand or change in system condition causes a progressive and uncontrolled drop in voltage. The main factor causing instability is the inability of the power system to meet the reactive power demand. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. A run-down situation causing voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of transmission network and the connected generation [5, 6].

A pattern recognition approach to detect the voltage instability in a power system in advance to its occurrence was implemented. This could help the operators to take remedial actions, and thus prevent the oncoming voltage collapse phenomenon. A pattern recognition software, Classification and Regression Trees (CART) and Regularized Least Squares Classification (RLSC) were deployed to develop the voltage stable and voltage unstable patterns. This was achieved by simulating voltage stable and unstable cases from a test system and then training the pattern recognition models to come up with patterns. These patterns were later validated by testing those using new cases which are not used for training.

Nigerian integrated 52 bus system was used as test system, it was modeled in Power System Simulator for Engineering (PSSE), and contingencies are applied to come up with the training and testing cases. MATLAB was used to develop RLSC algorithm and also to preprocess the data to be analyzed with CART.

METHODOLOGY
The method adopted to detect voltage collapse ahead of time consists of three phases as illustrated in the flow charts of figures1 to 3 respectively.
1. Modeling and simulation of test system: Here the power system dynamic response is captured.
2. Data Processing and feature extraction: The system variables around the instance of a disturbance that includes some pre-disturbance and post-disturbance variables are extracted and
3. Classification of voltage abnormality: Pattern recognition techniques phase-I of the methodology is applied to capture the dynamic response of the system. Here, capturing the system response means recording the system variables like bus voltage magnitudes, voltage angles, real and reactive powers, and generator rotor angles.

Dynamic response of the system can be captured by any one of the following two methods:
a. Using the equivalent system models and dynamic simulation tools, such as:
- Model the equivalent system for dynamic simulations in power system simulation tools such as PSSE.
- Perform the dynamic simulations on the modeled system using dynamic simulation tools.
- Capture the system response for all the variables of the system.

b. Collecting data from the field using Phasor Measurement Units (PMUs):
System data are captured from the PMU installed in the substations. These PMUs will record system variables with time stamp synchronized to Generating Plants Station (GPS) time clock

To detect voltage instability, the sequences of the first method are deployed on the Nigeria Integrated 330kV 52 bus power equivalent system as follows:

(a) **Capturing test system dynamic response(phase1):**Phase-I techniques have four steps to capture the test system dynamic response and these steps are presented as follows:

(i) **Test system modeled in Phase-I: Step A.** Flow chart for this step is shown in figure 1. In this step, the equivalent model data, such as, bus data and line data consisting of generator's output power, maximum and minimum reactive power limit of the generator, MW and Mvar peak loads, impedance of the lines, transmission line sizes, voltage and power ratings of the line and transformer data, and the nominal and critical voltages of each of the buses for the test system were collected from PHCN, and modeled in power system dynamic simulation software (PSSE). Multiple equivalent system models are created with different types of loads like induction motor loads, composite load models, etc. Once the system models are built, a dynamic simulation is performed on the system model for a base case (without applying any contingency). If the system dynamic response is stable, then the tasks in the next step of Phase-I will be performed.

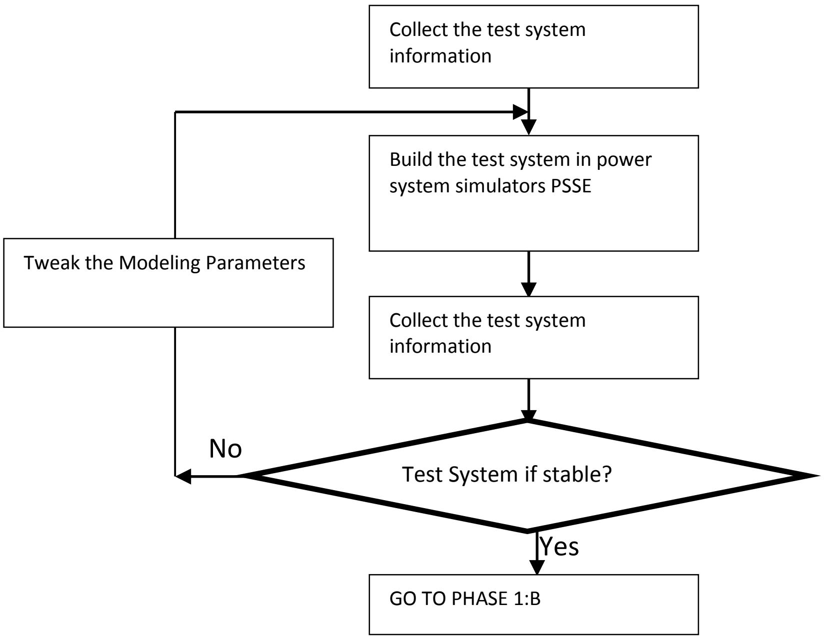

Figure 1: Flow chart for Phase-I: Step-A.

(ii) **Phase-I: Step-B**: In this step, the test system was stressed to determine critical contingencies by increasing load or disconnecting generating plants or disconnecting transmission lines. Flow chart for Phase-I: Step-B is shown in Figure 2. Contingency analysis was performed to determine the critical contingencies, and from those contingencies, voltage stable and voltage unstable cases are determined.

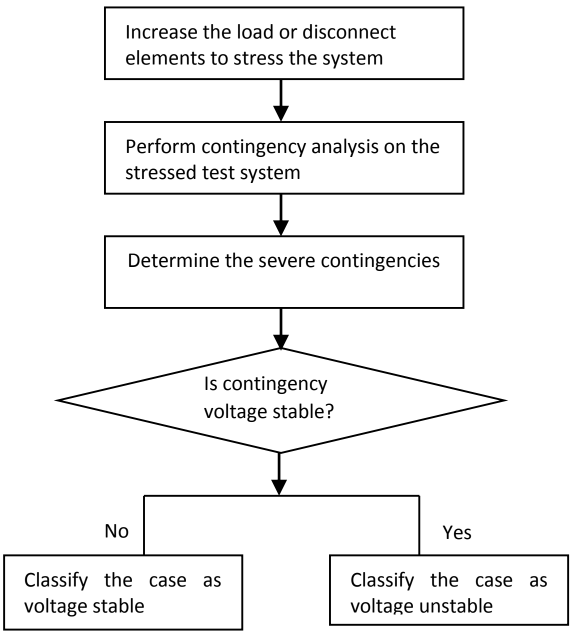

Figure 2: Flow chart for Phase-I: Step-B.

(iii) **Phase-I : Step-C :** After determining the critical contingencies, dynamic simulations are performed on voltage stable and voltage unstable cases in Phase-I: Step-C using the power system dynamic simulation software. Flow chart for Phase-I: Step-C is shown in Figure 3. Initially, the base case will be prepared for dynamic simulations, then dynamic simulations are performed on the contingencies found in Phase-I: Step-B and system parameters are captured. Voltage stability will be determined from the dynamic simulations performed on each contingency.

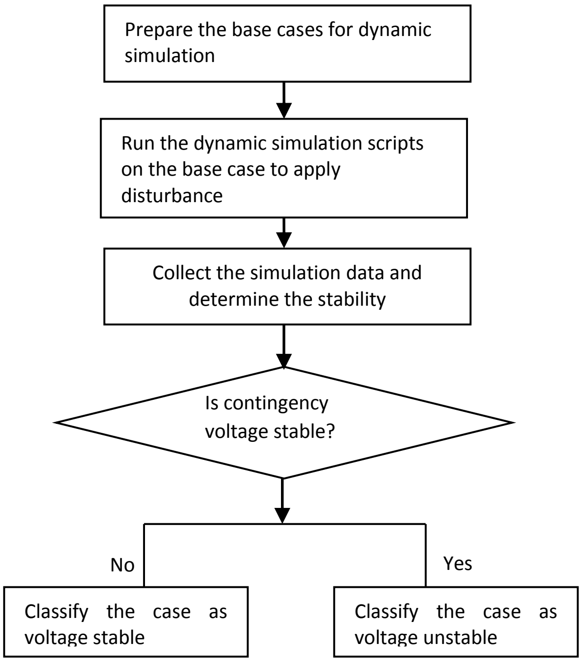

Figure 3: Flow chart for Phase-I: Step-C.

(iv) **Phase-1: Step-D:** In this step, system parameters or variables such as bus voltage magnitudes, voltage angles, real and reactive powers, and generator rotor angles are collected, modeled and simulated in PSSE software.

(b) Data Processing and Feature Extraction (Phase-II): Phase-II has two stages to pre-process the captured system dynamic response for Phase-III. Simulation parameters are extracted from the captured dynamic response of the system around the disturbance. This extracted system variables have a few seconds of the system dynamic response for pre-disturbance and post-disturbance data.

(c) Classification of Voltage Abnormality (Phase-III): The last phase of the method uses the pattern recognition techniques to predict the voltage stability from the power system dynamic response. Flowchart for Phase-III is shown in figure 4. Algorithmic and statistical pattern recognition techniques are programmed in this phase. These programmed methods are trained using the training samples extracted from Phase-II and a classifier to predict voltage stability was developed from the pattern recognition methods. This classifier was tested with the test samples extracted from Phase-II. If prediction using the classifier is accurate and efficient, then the prominent features and prominent system variables leading to this stability prediction are determined. If the developed classifier from pattern recognition method is not accurate, then problems relating to this defective classifier, either the pattern recognition method or the training samples used to train the pattern recognition method, are determined and corrected. In the last stage of Phase-III, the accurate pattern recognition methods to predict voltage collapse are determined.

3.1Pattern Recognition Procedure Formulation

Pattern recognition techniques such as, CART and RLSC are used to develop the voltage stable and unstable waveforms, as shown figure 4.

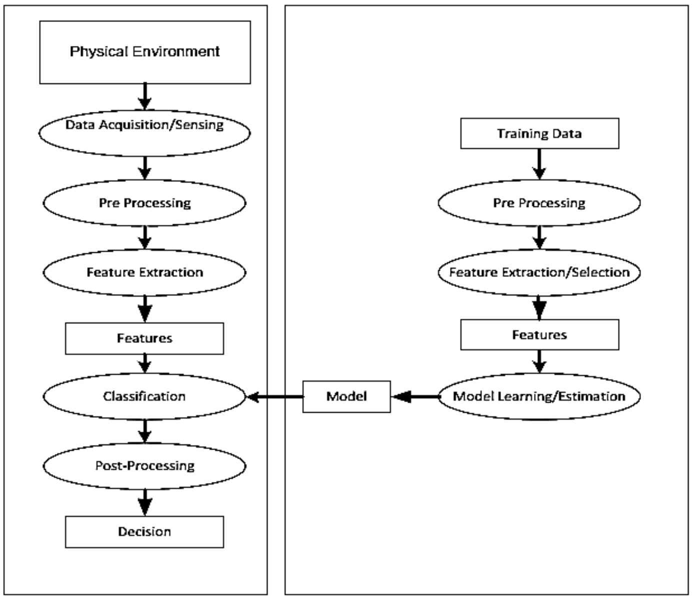

Figure 4: Flow chart of pattern recognition model (Phase III)

Mathematical formulations involved in RLSC and CART are presented as follows:

(a) RLSC Mathematical Formulation:

RLSC is a learning method that obtains solution for binary classification via Tikhonov regularization in a Reproducing Kernel Hilbert Space using the square loss function [7]. Let's assume X and Y are two sets of random variables, and the training set for pattern classification is S = (x_1, y_1), …., (x_n, y_n) and it satisfies $x_i \in R^n$ and $y_i \in \{-1,1\}$. For all i, the main goal is to learn a function *f(x)* while minimizing the probability of error described by the expression given in equation (1).

$$Pr\left(sgn(f(x))\right) \neq y \tag{1}$$

This can be found by solving the Empirical Risk Management (ERM) problem of finding the function in H_k (Hypothesis space) which minimizes

$$H_k = \frac{1}{m}\sum_{i=1}^{m}(f(x_i) - y_i)^2 \tag{2}$$

Minimizing, the hypothesis space H_k, for a fixed positive parameter γ, the regularized functional M_2 is computed as follows:

$$M_2 = \frac{1}{m}\sum_{i=1}^{m}(f(x_i) - y_i)^2 + \gamma\|f\|_k^2 \tag{3}$$

Reproducing Kernel Hilbert Space (RKHS), defined by the kernel .The solution for Tikhonov regularization problem can be solved by Representer Theorem, given by

$$f(x) = \sum_{i=1}^{n} c_i k(x, x_i) \tag{4}$$

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The first solution being the kernel matrix (K) is constructed from the training set S, as follows:

$$K = (k_{ij})_{1 \leq i, j \leq n} \tag{5}$$

$$k_{ij} = k(x_i, x_j) \tag{6}$$

The next step involves the computation of the vector coefficients c = $(c_1, c_2, \ldots c_n)^T$ by solving the system of linear equations as follows:

$$(K + n\lambda I)c = y$$

$$c = (K + n\lambda I)^{-1} y \tag{7}$$

Where y = $(y_1, y_2 \ldots y_n)^T$, I is the identity matrix of dimension n and finally, the classifier is:

$$f(x) = \sum_{i=1}^{n} c_i k(x, x_i) \tag{8}$$

The sign of this function $f(x)$ decides the class (+1 or −1) for x and its magnitude is the confidence in this prediction.

(b)Data Mining - CART:

Data mining is the process of extracting knowledge from data. The goal is to extract rules or knowledge from regularity patterns exhibited by the data. Decision Trees (DTs) is a method used for Data Mining [8]. CART is the methodology used to build the DTs.

3.2 Data Collection and Inputs:

The data used in this research were collected from Power Holding Company of Nigeria (PHCN) [9, 10, 11].

Table 1: Generating stations currently in operation in Nigeria.

S/N	STATION	STATE	TURBINE	INSTALLED CAPACITY (MW)	AVAILABLE CAPACITY (MW)
1	Kanji	Niger	Turbine	760	259
2	Jebba	Niger	Hydro	504	352
3	Shiroro	Niger	Hydro	600	402
4	Egbin	Lagos	Steam	1320	900
5*	Trans-Amadi	Rivers	Gas	100	57.3
6*	A.E.S (Egbin)	Lagos	Gas	250	211.8
7	Sapele	Delta	Gas	1020	170
8*	Ibom	Akwa-Ibom	Gas	155	25.3
9*	Okpai (Agip)	Delta	Gas	900	221
10	Afam I-V	Rivers	Gas	726	60
11*	Afam VI(Shell)	Rivers	Gas	650	520
12	Delta	Delta	Gas	912	281
13	Geregu	Kogi	Gas	414	120
14*	Omoku	Rivers	Gas	150	53

15*	Omotosho	Ondo	Gas	304	88.3
16*	Olorunshogo Phase I	Ogun	Gas	100	54.3
17*	Olorunshogo Phase II	Ogun	Gas	200	105.5
Total Power				**9,065**	**3,855.5**

Note: Generating stations marked* are the completed and functional independent power generation already in the Grid

Table 2: Buses for both existing and integrated 330kV power system project

S/N	BUSES	S/N	BUSES	S/N	BUSES
1	Shiroro	21	New Haven South	41	Yola
2	Afam	22	Makurdi	42	Gwagwalada
3	Ikot-Ekpene	23	Benin-Kebbi	43	Sakete
4	Port-Harcourt	24	Kanji	44	Ikot-Abasi
5	Aiyede	25	Oshogbo	45	Jalingo
6	Ikeja West	26	Onitsha	46	Kaduna
7	Papalanto	27	Benin North	47	Jebba GS
8	Aja	28	Omotosho	48	Kano
9	Egbin PS	29	Eyaen	49	Katampe
10	Ajaokuta	30	Calabar	50	Okapi
11	Benin	31	Alagbon	51	Jebba
12	Geregu	32	Damaturu	52	AES
13	Lokoja	33	Gombe		
14	Akangba	34	Maiduguri		
15	Sapele	35	Egbema		
16	Aladja	36	Omoku		
17	Delta PS	37	Owerri		
18	Alaoji	38	Erunkan		
19	Alaide	39	Ganmo		
20	New Haven	40	Jos		

Table 3: Transmission Line data of the 52-bus networks

S/N	Transmission line		Line Impedance		B (pu)
	From Bus	To Bus	R (pu)	X (pu)	
1	49	1	0.0029	0.0205	0.308
2	3	18	0.009	0.007	0.104
3	3	3	0.0155	0.0172	0.104
4	3	4	0.006	0.007	0.104
5	19	25	0.0291	0.0349	0.437
6	19	6	0.0341	0.0416	0.521
7	19	7	0.0291	0.0349	0.437
8	8	9	0.0155	0.0172	0.257
9	8	31	0.006	0.007	0.257
10	10	11	0.0126	0.0139	0.208
11	10	12	0.0155	0.0172	0.257
12	10	13	0.0155	0.0172	0.257
13	14	6	0.0155	0.0172	0.065

14	16	15	0.016	0.019	0.239
15	18	37	0.006	0.007	0.308
16	16	17	0.016	0.019	0.239
17	16	26	0.035	0.0419	0.524
18	16	3	0.0155	0.0172	0.257
19	19	21	0.006	0.0007	0.308
20	19	22	0.0205	0.0246	0.308
21	23	24	0.0786	0.0942	1.178
22	11	6	0.0705	0.0779	1.162
23	11	15	0.0126	0.0139	0.208
24	11	17	0.016	0.019	0.239
25	11	25	0.0636	0.0763	0.954
26	11	26	0.0347	0.0416	0.521
27	11	27	0.049	0.056	0.208
28	11	9	0.016	0.019	0.239
29	11	28	0.016	0.019	0.365
30	27	29	0.0126	0.0139	0.208
31	30	3	0.0126	0.0139	0.208
32	32	33	0.0786	0.0942	1.178
33	32	34	0.0786	0.0942	1.178
34	35	36	0.0126	0.0139	0.208
35	35	37	0.0126	0.0139	0.208
36	9	6	0.0155	0.0172	0.257
37	9	38	0.016	0.019	0.239
38	38	6	0.016	0.019	0.239
39	33	25	0.016	0.019	0.239
40	33	51	0.0341	0.0416	0.239
41	33	40	0.067	0.081	1.01
42	33	41	0.0245	0.0292	1.01
43	42	13	0.0156	0.0172	0.257
44	42	1	0.0155	0.0172	0.257
45	6	25	0.0341	0.0416	0.521
46	6	28	0.024	0.0292	0.365
47	6	7	0.0398	0.0477	0.597
48	6	43	0.0398	0.0477	0.521
49	44	3	0.0155	0.0172	0.257
50	51	25	0.0398	0.0477	0.597
51	45	41	0.0126	0.0139	0.208
52	51	47	0.002	0.0022	0.033
53	51	24	0.0205	0.0246	0.308
54	51	1	0.062	0.0702	0.927
55	40	46	0.049	0.0599	0.927
56	40	22	0.002	0.0022	0.308
57	46	48	0.058	0.0699	0.874
58	46	1	0.0249	0.0292	0.364
59	46	1	0.0205	0.0246	0.308
60	20	26	0.024	0.0292	0.365
61	20	21	0.0205	0.0246	0.308
62	50	26	0.006	0.007	0.104
63	26	37	0.006	0.007	0.104
64	3	21	0.0205	0.0246	0.257

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Table 4: Load data.

Bus No.	Load Data		Bus No.	Load Data	
	P(MW)	Q(Mvar)		P(MW)	Q(Mvar)
1	0.00	0.00	27	0.00	0.00
2	40.00	-10.00	28	0.00	0.00
3	0.00	0.00	29	120.00	80.00
4	140.00	30.00	30	130.00	-78.00
5	90.00	30.00	31	0.00	0.00
6	160.00	70.00	32	200.00	67.00
7	0.00	0.00	33	0.00	0.00
8	130.00	70.00	34	0.00	0.00
9	300.00	90.00	35	0.00	0.00
10	210.00	40.00	36	0.00	0.00
11	0.00	0.00	37	0.00	0.00
12	50.00	-20.00	38	0,00	0.00
13	100.00	-30.00	39	0.00	0.00
14	120.00	60.00	40	0.00	0.00
15	500.00	50.00	41	0.00	0.00
16	250.00	43.00	42	0.00	0.00
17	70.00	38.00	43	0.00	0.00
18	0.00	0.00	44	0.00	0.00
19	200.00	55.00	45	0.00	0.00
20	150.00	35.00	46	0.00	0.00
21	0.00	0.00	47	0.00	0.00
22	0.00	0.00	48	0.00	0.00
23	300.00	45.00	49	0.00	0.00
24	0.00	0.00	50	0.00	0.00
25	100.00	58.00	51	0.00	0.00
26	0.00	0.00	52	0.00	0.00

3.3 Design and Simulation of Nigeria 330kV Integrated 52 bus Power Network Using PSSE:
Power System Simulator for Engineering (PSSE) is composed of a comprehensive set of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions. The proposed method of determining voltage stability using Pattern Recognition was tested on Nigeria 330kV Integrated 52 bus power Network of figure 5. This network was designed in PSSE in a SIMULINK draft environment, as shown in figure 6. The dynamics simulation procedure was followed, and voltage stable and unstable cases were simulated by varying the load levels of table 4. The pattern recognition techniques were applied to extract the knowledge in the simulated data.

A portion of Nigeria 330kV integrated 52-bus power network of figure 6 was chosen for voltage stability. The transmission line branch from bus 6 (Ikeja West TS) to bus 9 (Egbin PS) was chosen for the study. The power flow was solved for the base loading of the network. Initially, N-1 contingencies were applied to the power network, which handles them effectively. This power network was stressed by increasing the real and reactive loads in steps and contingencies are applied for each loading level to observe the stability of the system. For each simulation, the following steps were adopted:

1. New loading condition was created by updating the real and reactive loads.
2. Power flow was solved.
3. The dynamic simulation was run for 10 seconds, without any contingency.
4. Contingency was applied after 10 seconds.
5. The simulation was continued till 100 seconds.

A python automation file was used for this purpose. The bus number was specified to accommodate load change and the amount of load (P and Q) for each run.
The bus at which the load is to be increased was determined. The load (P and Q) was then increased in steps and for each step, a specific contingency was applied and the stability was observed. Once an unstable case is encountered, the details are documented. Once the contingencies to be applied for that bus are completed, the analysis continued with the next bus.

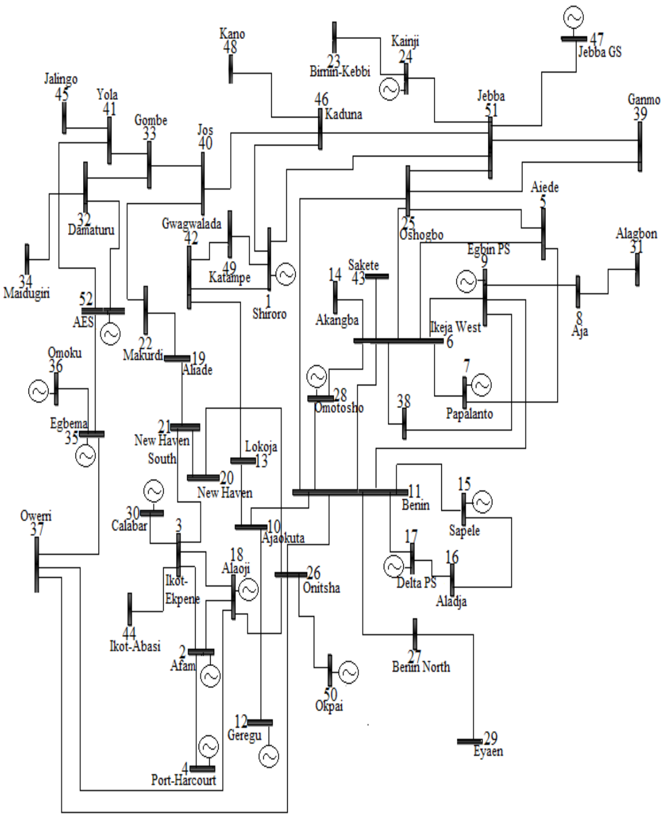

Figure 5: Nigeria 330kV Integrated 52 bus Power Network one line diagram

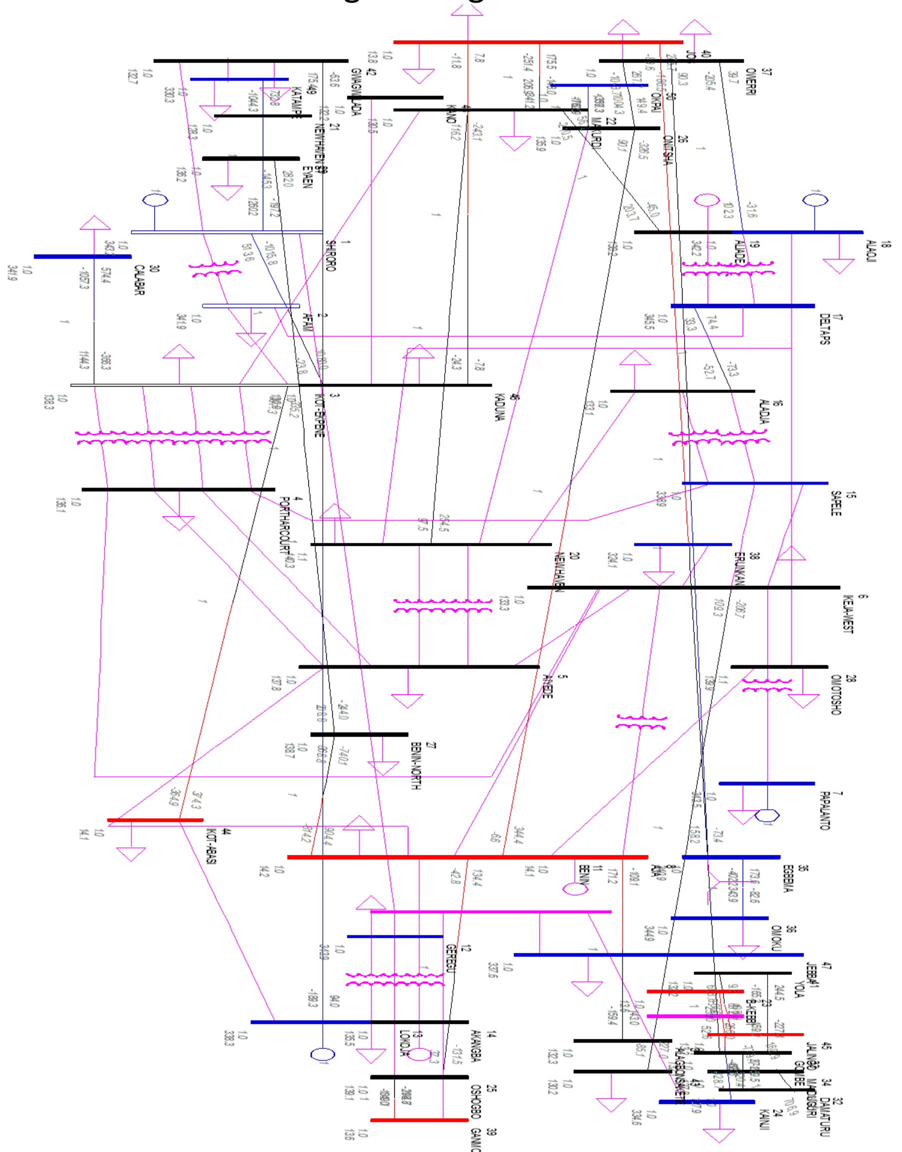

Figure 6: Simulink draft of the integrated 52 power bus network using PSSE

RESULTS AND DISCUSSION

The results obtained in this work showed the training cases of the RLSC and CART, voltage stable and unstable cases of 17 generators of Nigeria 330kV Integrated 52 bus Power Network.

Table 5: Training cases result of the RLSC algorithm and CART.

Case #	Bus No.	P (MW)	Q (MW)	Contingency	Stability
1	4	600	350	Line 6-11	Stable (+1)
2	4	550	300	Line 3-4	Stable (+1)
3	4	600	350	Line 3-4	Stable (+1)
4	4	700	450	Line 4-14	Stable (+1)
5	7	233.8	84	Line 8-9	Stable (+1)
6	7	233.8	84	Line 5-8	Stable (+1)

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7	7	400	350	Line 5-8	Stable (+1)
8	7	400	250	Line 6-11	Stable (+1)
9	7	233.8	84	Line 6-11	Stable (+1)
10	8	522	176	Line 8-9	Stable (+1)
11	8	600	300	Line 8-9	Stable (+1)
12	4	700	400	Line 3-4	Unstable (-1)
13	4	750	450	Line 6-11	Unstable (-1)
14	4	750	500	Line 4-14	Unstable (-1)
15	7	400	250	Line 8-9	Unstable (-1)
16	7	500	260	Line 5-8	Unstable (-1)
17	7	450	250	Line 6-11	Unstable (-1)

Table 5 showed the training cases result of the RLSC algorithm and CART. Five more cases were simulated in order to test the pattern recognition model developed from the training cases. The loading conditions and the contingencies applied for each testing case are shown in Table 6.

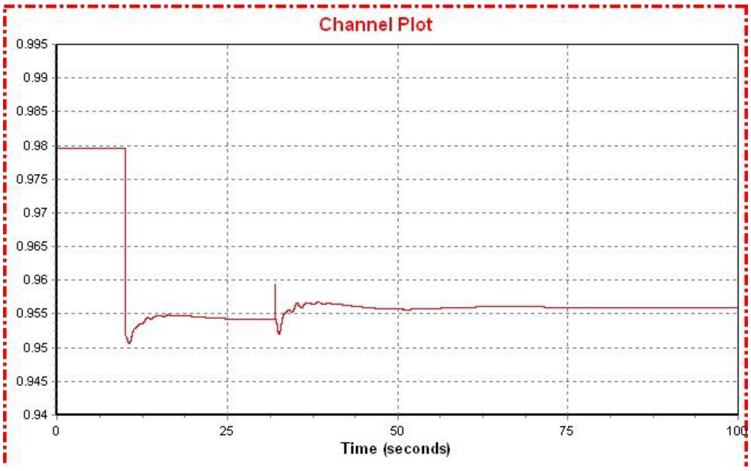

Figure 7: Voltage magnitude of training case 3 showing stable voltage (+1).

The voltage magnitude plot for case 3 showing stable voltage (+1) is shown in Figure 7. The load at bus 4 was increased and line 3 to 4 was disconnected after 10 seconds of dynamic simulation. Due to the loss of line 3 to 4, the voltage at bus 4 drops considerably as shown in the plot. This was due to increase in reactive power demand. The terminal voltages of generators 2 and 3 are restored by the excitation control. The increased reactive power demand was supplied by these two generators.

The Under Load Tap Changer (ULTC) connected at generator 8 between bus 6 and bus 31 operates after 20 seconds and the voltage at controlled bus, which is bus 6 was increased. This result showed an increase in the voltage level at bus 7. The voltage magnitude settles near 0.955pu as shown in figure 7.

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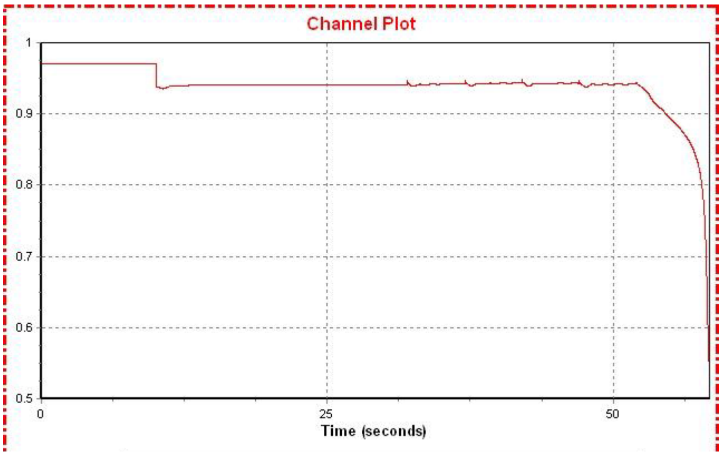
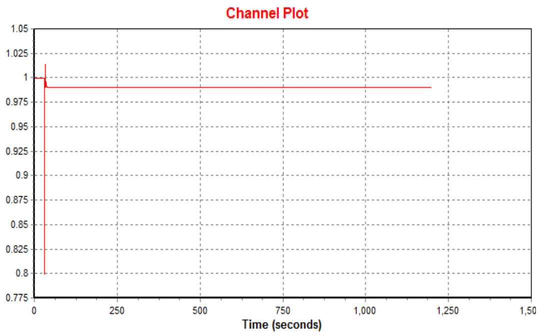


Figure 8: Voltage magnitude of Training Case 12 showing unstable voltage(-1).

The voltage magnitude plot for case 12 showing unstable voltage (-1) is shown in Figure 8.The load at bus 4 was increased, which stresses the system. After 10 seconds of simulation, the line3 to 4 was disconnected. This result showed a considerable decrease in voltage level at bus 4 due to the increase in reactive power demand. The terminal voltages at generators 2 and 3 are restored by the action of excitation control. The extra reactive power was supplied by these two generators. The Under Load Tap Changers (ULTCs) connected at generators 2 and 3 restored the voltages at the controlled buses (bus 6 and bus 9). With each tap change, the line I^2X and I^2R losses increase, which in turn decrease the voltage magnitude.

Table 6: Voltage stability result of the testing cases.

Case #	Bus	P (MW)	Q (MW)	Contingency	Stability
1	8	522	176	Line 5-8	Stable (+1)
2	8	700	450	Line 5-8	Stable (+1)
3	8	522	176	Line 6-11	Stable (+1)
4	8	650	350	Line 8-9	Unstable (-1)
5	8	700	650	Line 5-8	Unstable (-1)



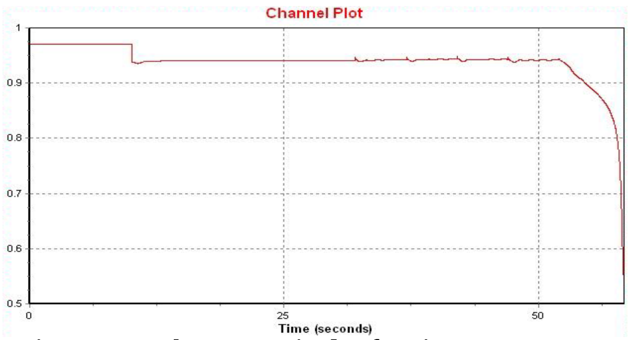


Figure 9: Voltage magnitude of testing Case 1 showing stable voltage(+1). *Figure 10: Voltage magnitude of testing case 5 showing unstable voltage (-1).*

The 17 training cases shown in Table 5 are used to train the RLSC algorithm. The data used was voltage magnitude from 0-15 seconds, the contingency was applied after 10 seconds. The developed model was used to predict the stability of the testing cases shown in table 8. Graphs showing the voltage magnitude testing case 1 for stable voltage(+1) and testing case 5 for unstable voltage(-1) as shown in table 8 are presented in figures 9 and 10 respectively.

CONCLUSION

The current Nigeria power grid is highly stressed due to the increased demand in electrical power without considerable addition of transmission lines. This brings a situation where the hazards of voltage collapse are highly possible to occur. This paper presents pattern recognition techniques, such as, Regularized Least Squares algorithm (RLSC) and Classification and Regression Trees (CART) for detecting voltage collapse ahead of time in power systems. This helps the operators to take remedial actions and eventually prevents the system from collapsing.

The work introduced the concept of the pattern recognition techniques in conjunction with Power System Simulator for Engineering (PSSE) and applied these techniques in voltage stability analysis for control of the Nigeria 330kV Integrated 52 bus Power Network. The method predicted correctly the voltage stability and instability cases for +1 and -1. The captured dynamics of the system within 10 seconds after a contingency was used to determine and detect the patterns. The three phases involved in achieving the voltage stability and instability cases of the test power network were presented.

The results of the dynamic simulations of the Nigerian integrated 52 bus test system and the system voltage stability for those simulations were obtained. The voltage stable and unstable dynamic simulation cases were divided into training and test set cases to validate the proposed methodology. CART and RLSC pattern recognition algorithms were trained using the training set and the trained algorithm was tested using the test set of the dynamic simulations.

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