Voltage Stability Improvement On Power Transmission Networks: A Case Study Of 330kv Power Transmission Networks In Nigeria

ABSTRACT

The 330kV power transmission system in Nigeria is associated with numerous problems ranging from voltage instability, ageing network, long and weak transmission lines and insulators, absence of protection schemes on the distribution network, lack of spinning reserve to compensate for power shortages, obsolete substation equipment, and higher power losses which substantially affect the reliability of power supply in Nigeria. This study aimed at analysing this scenario and to propose stability improvement measures in the power Network. Voltage instability is a major factor responsible for several system collapse and blackout experienced in the country. This work used necessary data obtained from the National Control Centre (NCC) of Transmission Company of Nigeria (TCN) for load flow simulation with the help of MATLAB R2021a software. Newton-Raphson iterative technique was used to carry out the load flow analysis due to its ability to converge faster with less iteration than Gauss-seidel and fast decoupled iterative techniques. The simulation results revealed that buses 4 (Akangba), 5 (Jos), 7 (Ikeja-west), 10 (Alagbon), 19 (Damaturu), 23 (Sakette), 28 (Ajah), 33 (Oke-Aro), 34 (Ayede) and 42 (Lekki) violate the acceptable limits as its voltage magnitude falls below the standard limit of 0.95-1.05pu. It was also observed that buses 6 (Kaduna), 13 (Yola), 16 (Gombe), 22 (Kano) and 34 (Ayede) are close to the point of instability as their voltage magnitudes are between 0.95 and 0.96 pu. These buses need urgent compensation if stability improvement in the entire Nigerian transmission system is to be achieved.

Keywords: Transmission systems, Disturbance, Voltage Stability, Voltage collapse, Fluctuation, Stability improvement

1 INTRODUCTION

Continuous growth in system interconnection, high demand for electrical energy, and economic and environmental constraints have made current power systems vulnerable to hazards of voltage instability [1]. Instability in voltage has led to abnormally high or low voltages and even voltage collapse as experienced in numerous interconnected power networks in Nigeria. The inability of the power system to maintain acceptable voltages in some or the entire buses in the system under standard conditions, when being interrupted or subjected to disturbance is referred to as voltage instability [2]. However, voltage stability can be referred to as the capacity of a power system to retain and maintain satisfactory voltages on all buses in a power system under normal operating conditions or when subjected to system interruption or disturbance [3].

This implies that the power system is stable if when subjected to disturbances, the supply voltages are close to normal operating values under standard conditions. Whereas instability or fluctuation is experienced in a power system when the magnitude of the voltages gradually or suddenly decreases due to an increase in load, loss of the major generating unit, switching operations, poor coordination within the protection scheme, high reactive power consumption during heavy load, tripping of transmission lines, loss of major equipment or high losses due to the remote location of power sources from load centres [4, 5]. The aim of any utility provider is to wheel power from the generating station to different substations with minimum losses. Power system voltage at all the busses should be kept constant. Investigation revealed that instability in the magnitude of voltage has been responsible for numerous grid failures and several blackouts that Nigeria as a nation has experienced in the past.

It is therefore essential that system synchronism and system voltage have to be maintained within stability limits if the quality of service rendered to the customers will be sustained. The stability limit refers to the maximum power that the network can carry from the generating station to the load centres without losing synchronism [6]. Stability in the system voltage relies on factors such as generator reactive power, characteristics of the load, and the nature of transmission lines. For reliable and maximum power system operation, the voltage magnitude and control of reactive power have to be such as to ensure that the actual voltage magnitude in all the buses is within the satisfactory and acceptable range [7]. The problems of voltage instability are connected with an increase in load on transmission lines, inadequate supply of local reactive power, and long-distance transmission of power [8]. Instability in voltage is caused by the power system's inability to satisfy the reactive power demand. It is a drop in voltage that could occur whenever a heavy load is experienced in the power system, and one of the results of instability in voltage is voltage collapse. An initial gradual continuous decline in voltage magnitude of the buses of power system and a sudden fall in the magnitude of voltage are characterized by voltage collapse [9].

According to the investigation carried out by Energy Vanguard in 2021 [10], Nigeria has experienced over 130 systems collapse in about eight years since 2013. Breakdowns of the cases indicate that the Nigeria power sector recorded a total of 45 partial grid failures and 82 total collapses since 2013 till date. In the year 2016, Nigeria witnessed seventeen (11) numbers of system collapse which is the highest ever recorded after the post-privatization of Power Holding Company of Nigeria (PHCN), and the least incidence is three (3) number in the year 2020, with four cases recorded on February 17, March 15, May 12, and 28 in 2021. The incidence that occurred in May 2021 was attributed to loss of generation from Shiroro power generation, a major generating station, while on July 28 blackout was caused by multiple tripping of 33kv transmission lines in some parts of the grid network [12]. The frequent grid failure experienced in the Nigerian 330kV transmission network could be further attributed to the aging network, sudden loss of generation, overloading of certain transmission corridors, obsolete substation equipment, lack of spinning reserve, operator mistakes, and non-functional protection scheme at distribution/downstream sector, weak transmission lines and insulators.

A series of events accompanying instability in voltage results in unsatisfactorily low voltage magnitude in many parts of a supply system. When the maximum loading points of the system approach, there is an increase in power losses in terms of the reactive and real power losses. Therefore, adequate reactive power support has to be provided in order to enhance and maintain stability of the voltage magnitude.

2 STRUCTURE OF 44 BUS 330KV NIGERIA TRANSMISSION SYSTEM

The single line diagram of the Nigerian 330kV network shown in Figure 1 consists of 17 generating stations and 44 load stations. The system can be divided into three major sections: South-East, South-West, and North sections [9]. The North is connected to the South through a double circuit line between Benin-Ajaokuta and another double circuit line between Ugwuaji-Markurdi while the West is linked to the South through one single circuit line from Oshogbo-Ihovbor, one single circuit line from Omotosho-Benin and another single circuit line between Egbin-Benin. Finally, the North interconnects with the West through a double circuit line between Jebba-Oshogbo and Single Circuit line from the Oshogbo-Ganmo transmission station.

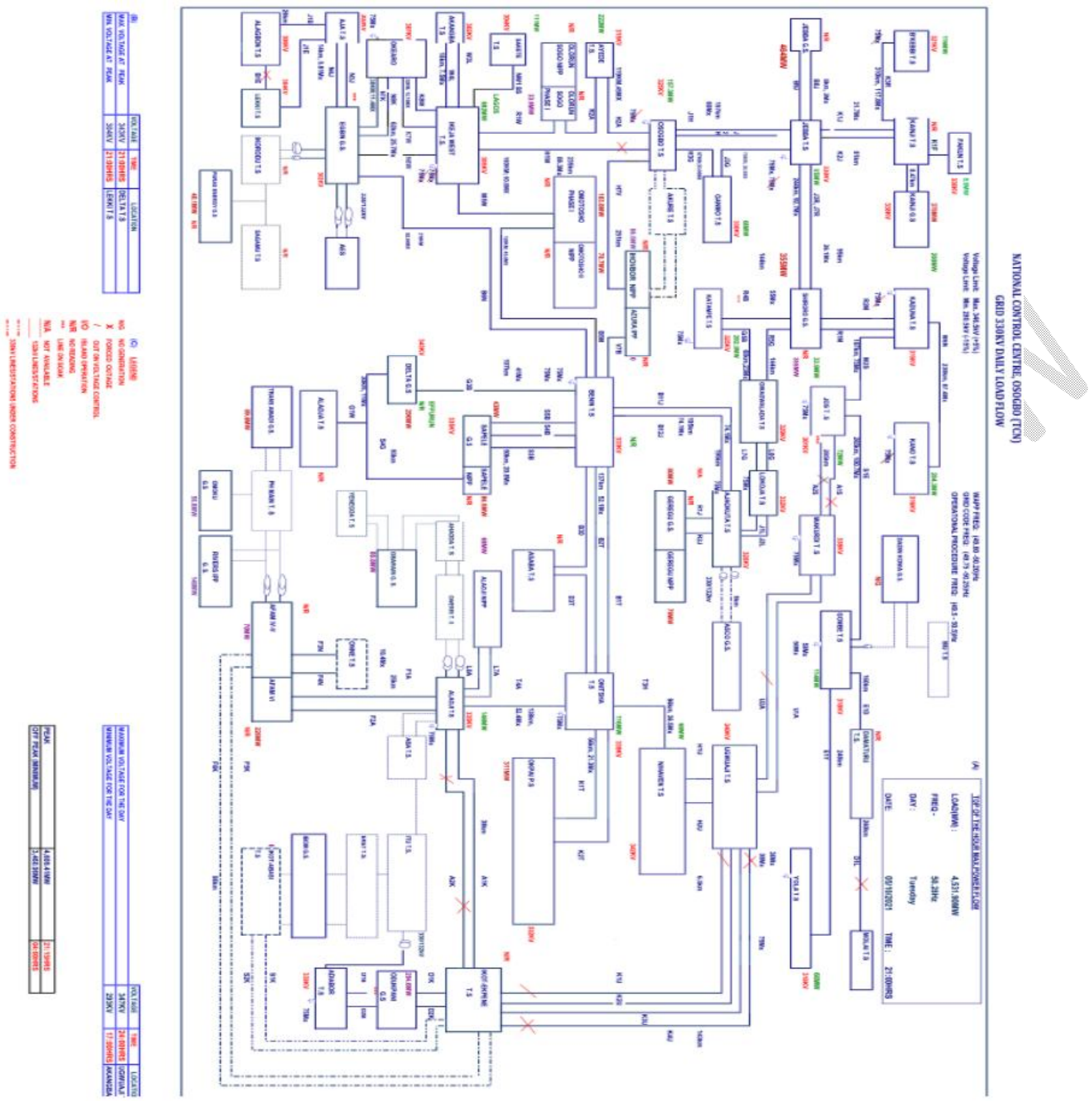

Fig 1: Single line diagrams of Nigerian 44 buses, 330kv transmission network. Source: Project Monitoring Unit (PMU) of Transmission Company of Nigeria [13].

3 RELATED WORKS

For decades the problem of Voltage stability has been studied. However, due to power system blackout which is related to the voltage collapse phenomenon that does occur frequently, Nigerian power system operators and researchers still have numerous issues to address. The problem of voltage stability is an important issue in the electricity industry in Nigeria. Voltage instability has been the major factor for several system collapses and consequently blackouts in Nigeria. The instability problem has become so complicated due to the constant growth in interconnections of systems and electrical energy demand across the country. System Stability solely depends on the reactive power of the generator that is, the voltage is stable when the generator reactive power is equal to the load reactive power. However, instability is experienced when the reverse is the case. Hence reactive power control is highly essential in order to maintain a good voltage profile and stability of the system voltage.

It is advisable that bus voltage within the power networks such as generating stations, switching substations, and load points should be held within acceptable limits. In an attempt to resolve some of the numerous issues or problems affecting the reliability and satisfactory operation of extra high voltage transmission networks and to improve power system stability, several research have been carried out in the past, some of which are briefly reviewed here.

Afolabi et al in 2020 [7] worked on transmission losses reduction and ways of improving system voltage using FACTS devices (STATCOM), with the case study of 132kV Bida power transmission system network considered. The result of their simulation shows that the 132kV Bida transmission power network is weak with voltage limit violations and higher losses of power. It also shows that STATCOM introduction reduces power losses, and enhances the magnitude of the voltage of the network and stability of the system under the faulty condition in comparison with the base case (without STATCOM placement).

Soufiane and Habib suggested using an evolutionary method to enhance the stability of voltage by FACTS Devices location [14]. They discussed new ways to enhance the stability of voltage by locating flexible AC transmission system devices in optimal positions. They used the Genetic Algorithm optimization technique to determine the proper positioning of the FACTS system in the power network and its effects in terms of voltage stability improvement.

Okwe et al [15] treated the enhancement of stability in voltage of Nigeria transmission network with the application of thyristor-controlled series capacitor (TCSC). They modeled the 330kv line with SIMULINK with and without placement of TCSC device and from this obtained the line parameters. The results of the work showed significant improvement in terms of voltage stability, line losses, and transmission efficiency. Ignatius et al, 2017 assessed the load flow of a 330kV power transmission network in Nigeria with a power flow study of the grid network using the MATLAB/SIMULINK software [16]. Their results affirmed the numerous problems the Nigeria 330kV grid network is associated with and indicated that high losses of reactive power exist in the network. They confirmed that compensation for reactive power is essential and suggested additional lines and more switching substations be introduced in the network.

Anita and Anant, 2021 reviewed the use of various FACTS technology on electrical power networks [6]. They applied different flexible AC transmission systems (FACTS) technology such as static synchronous compensator (STATCOM), Unified power flow controller (UPFC), Thyristor controlled series compensator (TCSC), interline power flow controller (IPFC), and Static synchronous series compensator (SSSC) on the network and thereby analyzed the effects of compensation on real and reactive power.

Mbunwe and Ekwue worked on power system compensation using Multi-type FACTS controllers on a 48-bus Nigeria 330kV transmission system [17]. Installation of static VAR Compensator (SVC) or thyristor-controlled series compensator (TCSC) separately was compared with combining both SVC and TCSC in the system. Power System Analysis Toolbox (PSAT) in MATLAB was used to achieve voltage magnitude, losses in terms of active and reactive power, and results of simulation with and without FACTS devices placed optimally with the use of voltage stability sensitivity factor (VSSF) shows the high decrease of reactive and real power losses with SVC and TCSC combined against SVC or TCSC alone respectively. They showed that combining SVC and TCSC is on compensation compared to standalone FACTS devices.

Adebayo *et al*, studied enhancing steady-state voltage stability on the Nigerian 330kv power grid system by making use of a static synchronous series compensator (SSSC) [9]. A static synchronous series compensator was applied to control buses with low voltage in the 330kv transmission grid. Analysis of power flow was done using a MATLAB-based program on the 28-bus Nigeria 330kV system and the effects with and without static synchronous series compensator (SSSC) was carried out. The result was that the applications of SSSC satisfactorily improved the bus voltages to acceptable limits.

Most existing publications focus on stability improvement of the power system through the application of FACTS devices such as Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Static VAR Compensator (SVC), thyristor-controlled series compensator (TCSC) and so on. Very little attention has been paid to the use and effects of UPFC in improving grid networks like the turbulent Nigeria 330kV power transmission network. Also, the behavior of the system with and without the placement of FACTS devices requires further studies. The UPFC model has not been explained adequately with respect to its practical application for the improvement of voltage stability in the Nigeria 330kV grid system. Hence this work focused on employing UPFC devices to address these issues.

4 MATERIAL AND METHOD

Data for the following required parameters were obtained from the National Control Centre of Transmission Company of Nigeria (TCN) located in Osogbo, in the South-Western State of Osun: number of buses in the network, voltage magnitude of buses across the network, phase angle of each line for the entire Nigeria grid, transformers, and generators data.

In this study the modelling and simulation of the entire 44 buses of the 330kV transmission system was carried out using the MATLAB software. To determine the phase angle, reactive and active power as well as magnitude of voltage in the system, voltage magnitude was kept at 330kV. Newton-Raphson iterative technique which involved solving a set of non-linear algebraic equations was deployed in solving the load flow problems.

Formation of power flow equation

The static load flow equations which are generally non-linear equations can be obtained as follows [6]:
If the complex power injected by the generating source into the i^{th} bus of a power system is given by:

$$S_i = P_i + jQ_i = V_i I_i^*, \quad i = 1,2,3,\dots,n \tag{1}$$

where V_i = Voltage at the i^{th} bus with respect to ground,

I_i^* = Complex conjugate of the source current I_i

since it is convenient to handle flow using I_i rather than I_i^*, taking the complex conjugate of equation (1) we have:

$$S_i^* = P_i - jQ_i = V_i^* I_i, \qquad i = 1,2,3,\dots,n \tag{2}$$

With

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k \tag{3}$$

substituting equation (3) into equation (2) gives:

$$S_i^* = P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k, \qquad i = 1,2,3,\dots,n \tag{4}$$

Equating the real and imaginary parts, we have the real and reactive powers respectively:

$$(P_i) = \mathrm{Re}\left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\} \quad (5)$$

$$(Q_i) = -I_m \left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\} \quad (6)$$

The voltage at the bus i^{th} can be expressed into polar form:

$$V_i = V_i < \delta_L \quad (7a)$$

$$V_i^* = V_i < -\delta_L \quad (7b)$$

Similarly: $$Y_{ik} = Y_{ik} < \theta_{ik} \quad (8)$$

Therefore, the real power can be expressed as:

$$P_i = V_i \sum_{k=1}^{n} V_k Y_{ik} \cos(\theta_{ik} + \delta_k - \delta_L) \quad (9)$$

and the reactive power expressed as:

$$Q_i = -V_i \sum_{k=1}^{n} V_k Y_{ik} \sin(\theta_{ik} + \delta_k - \delta_L) \quad (10)$$

Equations (9) and (10) are regarded as static load flow equations.
The set of real and imaginary components of the reactive and real components of the bus voltage were put into the Jacobian matrix to iteratively solve 2(n – 1) set of simultaneous equations

5 RESULTS AND ANALYSIS

With the simulation of the load flow data obtained from the National Control Centre of TCN, buses whose voltage magnitudes violate the acceptable limit of 0.95-1.05 within the system were identified. Newton-Raphson iterative technique was used for the load flow simulation and the results obtained revealed that buses 4 (Akangba) is 0.91pu, 5 (Jos) is 0.91pu, 7 (Ikeja-West) is 0.92pu, 10 (Alagbon) is 0.92pu, 19 (Damaturu) 0.93pu, 23 (Sakette) is 0.92pu, 28 (Ajah) is 0.91pu, 33 (Oke-Aro) is 0.92pu, and 42 (Lekki) is 0.92pu. These all violated the acceptable voltage limit as their magnitudes fell below 0.95-1.05pu.

It was also observed that buses such as Kaduna, Yola, Gombe, Ayede and Kano are close to the point of instability as their voltage magnitudes are between 0.95 and 0.96pu. There is urgent need for reactive power compensation on these buses to avert future failure. The bar chart for the simulation is shown in Figure 2 with Figure 3 showing the bus voltage against the bus numbers. These results reveal the level of instability the Nigeria transmission network is currently experiencing and the need to incorporate compensation devices such as Flexible Alternating Current System (FACTS) on the affected buses so as to avert the frequent grid failure as experienced in the country.

Table 1: Newton-Raphson Load-flow Analysis for the Base Case study

Bus no	Bus name	Voltage magnitude (Pu)	Phase angle (Degrees)	Generation (MW)	Generation (MVAR	load (MW)	load (MVAR)
1	Egbin	1.00	0	602	278	442	198.0
2	Kainji	1.02	0	370	227.5	115	69.4
3	Jebba GS	1.00	0	464	286.4	34	19.2
4	Akangba	0.91	0	0.00	0.00	210	130.2
5	Jos	0.91	0	0.00	0.00	72.9	45.0
6	Kaduna	0.95	0	0.00	0.00	293	181.65

7	Ikeja-west	0.92	0	0.00	0.00	882	413.2
8	Shiroro	1.01	0	355	225	122	92.1
9	Benin	1.00	0	0.00	0.00	260	158.0
10	Alagbon	0.92	0	0.00	0.00	50	32.0
11	Onitsha	1.02	0	0.00	0.00	116	52.4
12	Afam	1.02	0	570	300.4	150	93.0
13	Yola	0.96	0	0.00	0.00	50	32.3
14	Gerugu	1.01	0	214	132.67	60	37.2
15	Birni Kebbi	0.97	0	0.00	0.00	116	71.8
16	Gombe	0.96	0	0.00	0.00	114	52.0
17	Sapele	1.01	0	420	260.38	150	93.0
18	Ajaokuta	0.98	0	0.00	0.00	30	18.6
19	Damaturu	0.93	0	0.00	0.00	80	45.6
20	New Haven	1.03	0	0.00	0.00	68	36.5
21	Alaoji	1.01	0	383	237	146	88.2
22	Kano	0.95	0	0.00	0.00	204.3	87.4
23	Sakete	0.92	0	0.00	0.00	120	74.3
24	Okpai	1.00	0	311	189.6	100	62.0
25	Katampe	0.98	0	0.00	0.00	202.3	75.0
26	Oshogbo	0.98	0	0.00	0.00	157.3	75.0
27	Jebba TS	1.00	0	0.00	0.00	70	43.4
28	Ajah	0.91	0	0.00	0.00	274	169.9
29	Olorunsogo	0.92	0	336	208.3	120.4	77.2
30	Omotosho	1.00	0	128	86	262.5	154.0
31	Delta PS	1.03	0	296	155	260	161.2
32	Ganmo	1.00	0	0.00	0.00	68	26.6
33	Oke-Aro	0.93	0	0.00	0.00	52	32.24
34	Ayede	0.95	0	0.00	0.00	222	108.5
35	Onne	1.00	0	0.00	0.00	72.3	44.7
36	Lokoja	1.00	0	0.00	0.00	85	53.2
37	Benin kebbi	0.97	0	0.00	0.00	116	57.8
38	Fakun	1.02	0	0.00	0.00	8.9	4.4
39	Sapele	1.01	0	0.00	0.00	43	27.0
40	Gwagwalada	0.99	0	0.00	0.00	170	105.4
41	Uawuaji	1.03	0	0.00	0.00	55	34.0
42	Lekki	0.92	0	0.00	0.00	72	45.9
43	Adiabor	1.02	0	0.00	0.00	76	44.1
44	Ikot-ekpene T/S	1.02	0	0.00	0.00	66	39.4

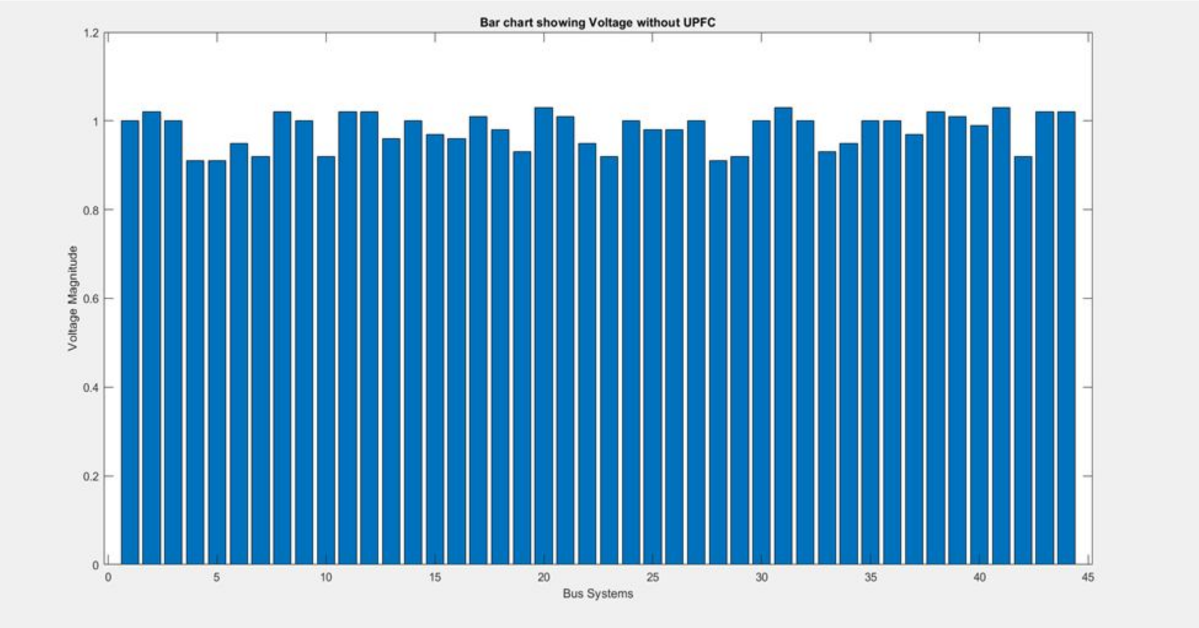

Fig 2: Bar chart of Bus Voltages against Bus Number without compensation.

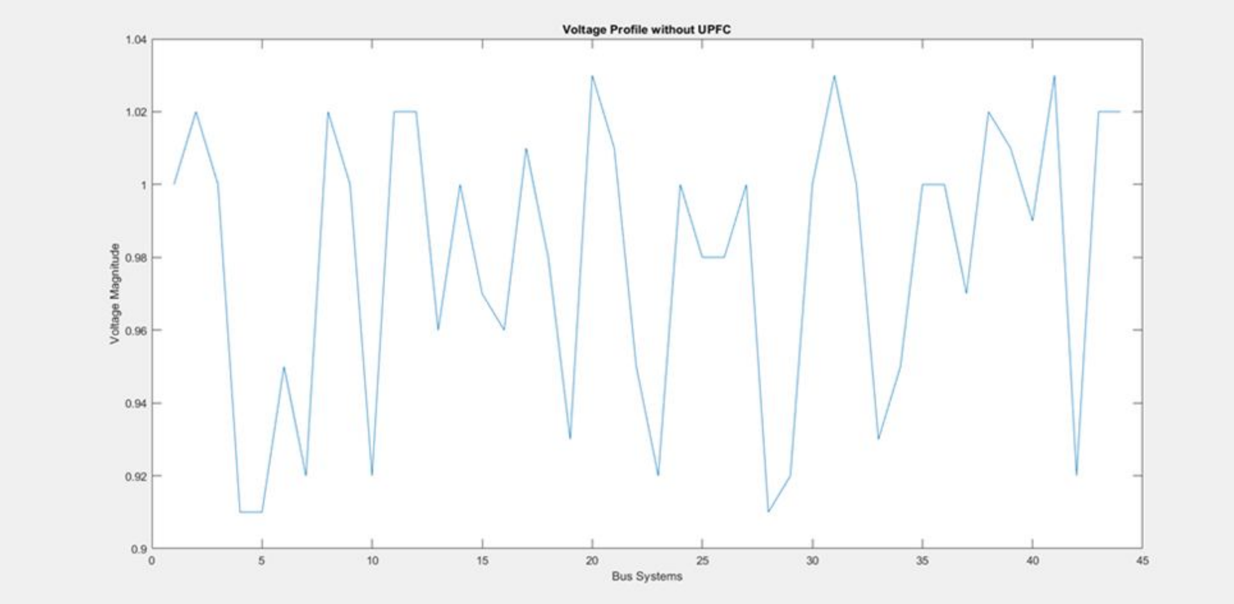

Fig 3: Plot of Bus Voltages against Bus Number without compensation.

6 CONCLUSIONS

In this work, the existing forty-four (44) bus system in TCN was considered for voltage instability system. The buses whose voltage magnitude were discovered to be below acceptable limits were identified as buses 4 (Akangba), 5 (Jos), 7 (Ikeja-west), 10 (Alagbon), 19 (Damaturu), 23 (Sakette), 28 (Ajah), 33 (Oke-Aro), 34 (Ayede) and 42 (Lekki) as their voltage magnitude violate the acceptable limits of 0.95-1.05pu. There is therefore, need for these buses to be improved upon through the incorporation of modern compensation devices such as the use of FACTS devices in order to improve their voltage magnitudes and thereby improve the overall system stability of the entire grid system.

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