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Improved Under-Voltage Load Shedding Scheme in Power System Network for South Eastern Nigeria

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Abstract

This paper presents an Improved Under-Voltage Load Shedding Scheme in Power System for South Eastern Nigeria distribution network. The south eastern Nigeria distribution network was first modeled and its load flow regenerated using Newton Raphson iterative load flow method for all 203 load buses in the network. The aim is to improve the existing network's bus voltage profile with the use of various under-voltage load shedding schemes for improved power and its effect of the system voltage profile was analyzed and recorded for 100%, 60% and 50% load shedding case studies. Results showed an improvement in the entire network bus voltage level after the load shedding scheme between 10.34 kV to 11.22 kV for 11 kV buses and between 31.02 kV to 33.66 kV for 33 kV buses indicating the nominal voltage level. It showed an increment in the total number of nominal voltage buses of each case study, from 22 buses at 100% load demand to 105 buses when 40% of the load has been shed to finally, 126 buses when 50% of the load has been shed in the 50% load demand scenario A and B. Finally, the number of under-voltage buses decreases to 3 and 7 buses in Scenario A and B respectively when 50% of the total load demand has been shed by Enugu Electric Distribution Company (EEDC).

1. Introduction

The Southeast distribution network of Nigeria under Enugu Electricity Distribution Company (EEDC) has eighteen districts namely Abakaliki, Ogui, Abakpa, Awkunanaw, Nsukka, Mbaise, New Owerri, Orlu, Owerri, Ogbaru, Onitsha, Ogidi, Nnewi, Awka, Ekwulobia, Aba, Ariara, Umuahia and covers five (5) states [1, 2]. The southeast distribution network consists of one hundred and thirty-eight (138) buses out of which seventy (70) are 11 kV buses, sixty-seven (67) are 33 kV buses and one (1) is 6.6 kV bus, operating at under-voltage (i.e., below 94% of the bus nominal voltage), at marginal-voltage (i.e., between 94% and 98% and between 102% and 105% of the bus nominal voltage) and at nominal voltage (i.e., between 98% and 102% of the bus nominal voltage) [3].

Load shedding is a final measure used to avoid a wide area voltage collapse when all other effective means are exhausted. Moreover, new static relays with greater precision and stability can achieve secure, coordinated, system wide automatic load shedding and load restoration [4].

1.1 Under Voltage Load shedding (UVLS)

Under voltage load shedding is carried out in order to arrest excess voltage sag below nominal value. Load shedding schemes can also be classified with regards based on implementation:

1. Static Load Shedding Scheme: load shedding is fixed predetermined block sizes.
2. Semi-adaptive Load Shedding Scheme: load shedding taking magnitude of disturbance into account to differentiate between small and large disturbance so as to avoid over shedding.
3. Adaptive Load Shedding Scheme: load shedding in variable block sizes determined in real-time depending on imbalance prevailing in the system.
4. Centralized Load Shedding Scheme: Load shedding taking into account real and active power imbalance, wide area addition to determination of dynamic block sizes to be shed.

Static Load Shedding curtails constant block of load at every stage. The calculation of time to shed the load is acquired from the system overload and change of under voltage levels. In static load shedding scheme, it is better to have more stages, but with smaller load in each stage, to minimize over shedding. Moreover, tripping a big block of loads at one time will have a large impact on an already weakened system. However, the drawback is that it takes longer time to stabilize the voltage level [5].

When the system condition has more generation than the sum total of total load demand and total system network losses then Over Voltage will occur in the system. While, if the system condition has more sum total of total load demand and total system network losses than generation then Under Voltage will occur in the system. Whereas, if the system condition has the sum total of total load demand and total system network losses equal generation then the system voltage will be nominal [6].

Several researchers have carried out work on under-voltage load shedding scheme in power system network. An optimal load-shedding algorithm was developed by [7] in order to provide voltage stability. This was carried out over the IEEE 14 and 118 bus test systems and solved using a mathematical (GAMS/CONOPT) and two heuristic (PSO and GA) methods. [8] Illustrated an optimal load shedding strategy for Selçuk University power system with distributed generation. They demonstrated an intelligent load shedding strategy in electrical system of Selçuk University medical faculty consisting different type and size of loads and being supplied by a distributed generator with the aid of under frequency relays and programmable logic controller (PLCs). An optimal under voltage load shedding based on voltage stability index carried out in an IEEE 14 bus test system was presented by [9] based on classical criterion for the under voltage load shedding, identifying the load to disconnect by considering bus voltage level, and a simplified voltage stability index SVSI, which identifies critical buses in the system. An advanced method for under voltage load shedding by incorporating a UVLS Logic relay design in MATLAB Simulink environment to provide voltage stability was proposed by [10]. [11] Described the improved load shedding scheme considering distributed generation. Their work illustrates that the conventional under frequency load shedding (UFLS) faces many challenges and proposed new UFLS schemes. These schemes utilize directional relays, power flow through feeders, wind, and photovoltaic (PV) measurements to optimally select the feeders to be disconnected during load shedding. [12] Utilizes an under frequency and under voltage load shedding schemes by using their indices in improving voltage level at injection substations. This helps in achieving a more comprehensive, effective, and reliable load shedding strategy. This was carried out on on 3-machine 9-bus test system. [13] Proposed an under-voltage load shedding (UVLS) scheme to prevent voltage collapse in a microgrid (MG) by using voltage stability index to rank loads according to their index values. [14] Presented a multi-stage under-voltage load shedding scheme using a DIgSILENT power factory software to stabilize the power system network. The power flow study is deployed to determine the optimal system operating conditions of the IEEE 39 bus system by using PV and QV curve method to determine the critical operation point before the occurrence of voltage instability. A study which analyzed the load shedding scheme through the use of empirical measurement tools and load-flow simulation techniques were carried out by [15]. This was done in order to determine the effective load shedding strategies to reduce unnecessary overload for achieving dynamic system stability of the electric power system network. In [16], an islanded microgrid with high penetration of renewable energy sources is analyzed, and then artificial bee colony (ABC) algorithm is applied for optimal load shedding on a standard IEEE 30-bus system on a MATLAB platform.

From the reviewed literatures, it is seen that analysis and simulation on improved under-voltage load shedding scheme in south eastern Nigeria power system distribution network is of great important for determining voltage profile of a given load demand with subsequent increment in the total number of nominal voltage for the buses.

2. Methodology

The following materials were used in achieving an Improved Load Shedding Scheme in Power System for Southeastern Nigeria

I. Data from Enugu Electric Distribution Company (EEDC).
II. ETAP 19.0 analysis software.

2.1 Newton Raphson Iterative Load Flow Method

The Newton-Raphson method is a powerful method of solving non-linear algebraic equations and it has better and faster convergence characteristics [17].

Consider a set of n non-linear algebraic equations.

$$f_i(x_1, x_2, \dots\dots\dots, x_n) = 0 \quad , \quad i = 1, 2, 3, \dots, n \tag{1}$$

Assuming the initial values are $x_1^0, x_2^0, \dots\dots\dots, x_n^0$. Let $\Delta x_1^0, \Delta x_2^0, \dots\dots\dots, \Delta x_n^0$ be the corrections to be added to the initial values to give the actual solution (1) becomes.

$$f_i(x_1^0 + \Delta x_1^0, x_2^0 + \Delta x_2^0, \dots\dots\dots, x_n^0 + \Delta x_n^0) = 0 \quad , \quad i = 1, 2, 3, \dots, n \tag{2}$$

Expanding the Taylor series and solving we have;

$$\text{Hence,} \quad f^0 + J^0 \Delta x^0 = 0 \tag{3}$$

$$\text{And,} \quad f^0 = -J^0 \Delta x^0 \tag{4}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} * \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{5}$$

Since the R/X ratio of the line is very low J_2, J_3 is approximately zero.

The real power mismatch, ΔP is very sensitive to changes in the phase angle $\Delta\delta$ and less sensitive to changes in the voltage magnitude, $\Delta|V|$. The reactive power mismatch, ΔQ is very sensitive to changes in the voltage magnitude, $\Delta|V|$ and less sensitive to changes in the phase angle $\Delta\delta$. Hence Equation (5) becomes,

$$\Delta P = J_1 * \Delta\delta \tag{6}$$
$$\Delta Q = J_4 * \Delta|V| \tag{7}$$

Further solving the new estimated for bus voltage magnitude and angles are,

$$|V_i|^{(r+1)} = |V_i|^{(r)} + \Delta|V_i|^{(r)} \quad (8)$$

$$\delta_i^{(r+1)} = \delta_i^{(r)} + \Delta\, \delta_i^{(r)} \quad (9)$$

2.2 The Under Voltage Load Shedding Algorithm

When the given power supply from the transmission center cannot meet load demands, the appropriate shedding scheme will be carried out under operating constraints, achieving safe transition to normal state.

The load flow simulation is then developed for different Case Studies depending on how much of the overall load demand is been met. The simulation is then repeated for different case studies while alternating the combination of loads using the priority number until, the system condition of the sum total load demand and total system network losses equals to the generation of the system, then the system voltage will be nominal. Hence, elimination under voltage condition.

Each Case can be divided into two categories based on the Load Shedding Case Study Analysis above: Scenario A and Scenario B.

- **A.** Load Shedding Scenario A: for 100% (Full Load Demand) for Case Study I, 60% Load Demand for Case Study II and 50% Load Demand for Case Study III of the total load demand of the EEDC distribution network.
- **B.** Load Shedding Scenario B: for 0% Load Demand for Case Study I, 40% Load Demand for Case Study II and 50% Load Demand for Case Study III of the total load demand of the EEDC distribution network.

This Load Shedding Scenarios are done with consideration to the Load Feeder Classification Priority number and the 33kV Bus to Bus distance. This is done to achieve the following:

- ✓ Optimal Bus Voltage Level of between 94% to 102% (i.e., 10.34 kV to 11.22 kV), of the nominal voltage level of each scenario required for distribution, thereby reducing bus Under-voltage power distribution.
- ✓ To reduce EEDC distribution network losses to the barest minimum while maintaining full network distribution coverage and adequate voltage level required for distribution.

The minimum occurring losses is required so as to ensure that losses that would have occurred from distribution to load centers across multiple long distances of distribution lines are properly conserved and utilized throughout the network, hence enhancing voltage stabilization for optimum distribution in the EEDC Network System.

2.3 Load Feeder Priority Number

Load feeder priority number are numbers assigned to each feeder based on the load demand, region serviced, revenue generated by the feeder and hours the feeder is being loaded. The EEDC Feeder classification types are.

- **i.** Critical Load Feeders – in service for up to 12 – 18 hours in a day.
- **ii.** Essential Load Feeders – in service for up to 8 – 12 hours in a day.
- **iii.** Normal Load Feeders – in service for up to 6 – 9 hours in a day.
- **iv.** Least Essential Load Feeders – in service for up to 3 – 6 hours in a day.

The load feeder priority number assigned are given in Table 1 as:

Table 1: Load classification type and priority

Load Classification Type	**Priority**	**Load Shedding Scheme**	
		Scenario A	**Scenario B**
Critical	**1**	**ON**	**OFF**
Essential	**2**	**OFF**	**ON**
Normal	**3**	**OFF**	**ON**
Least Essential	**4**	**ON**	**OFF**

2.4 Network for the Analysis

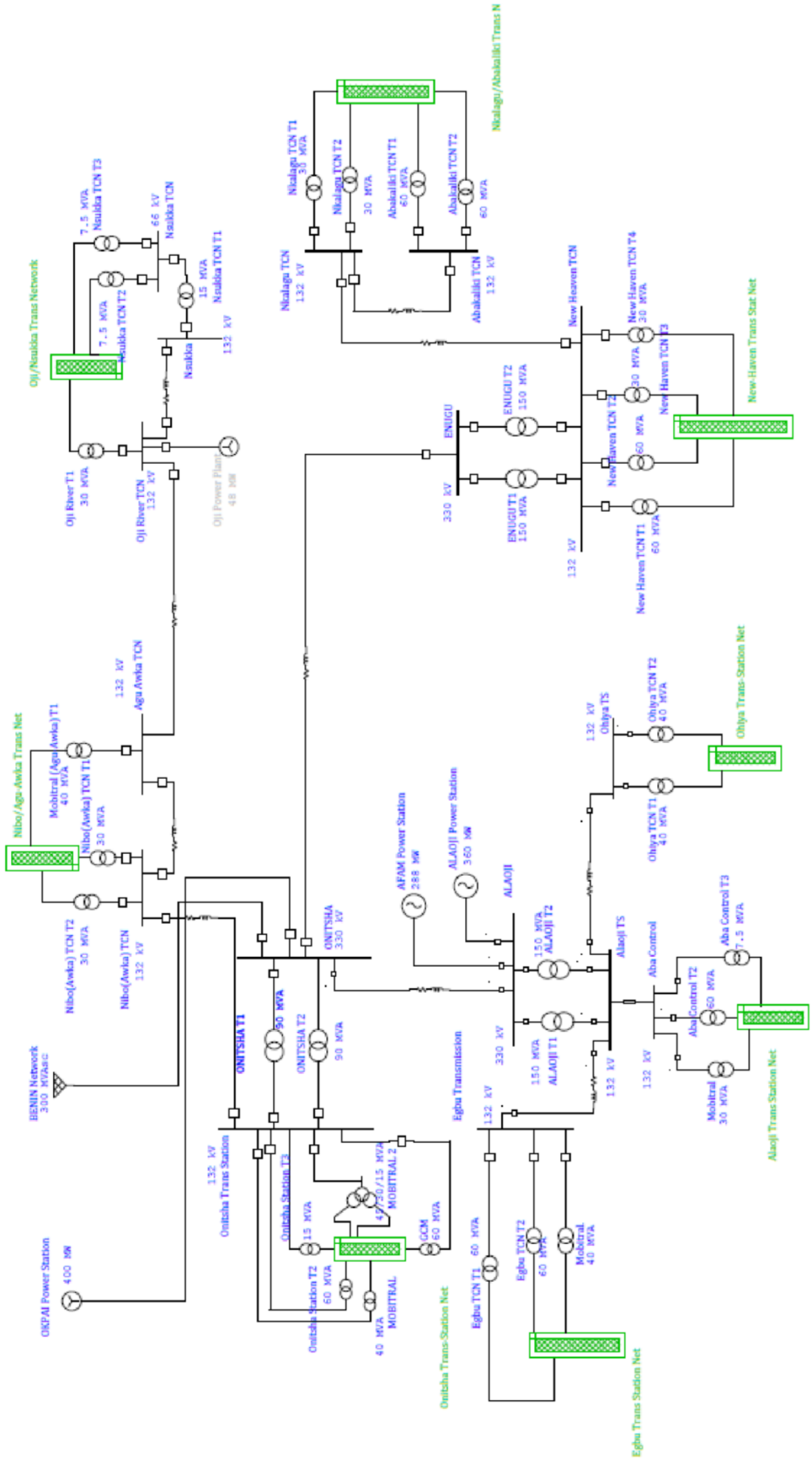

Figure 1: South east distribution network

The bus structure of the southeast distribution network and its sub networks are shown in the Figure 1.

3. Results and Discussion

3.1 When Network is Operating on Full Load Operation

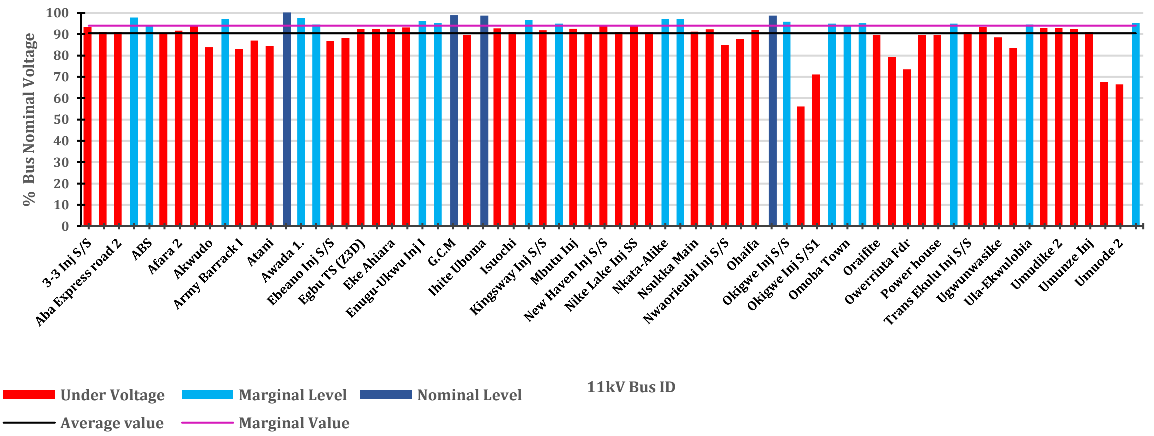

Figure 2: 11kV buses voltage profile for full load case

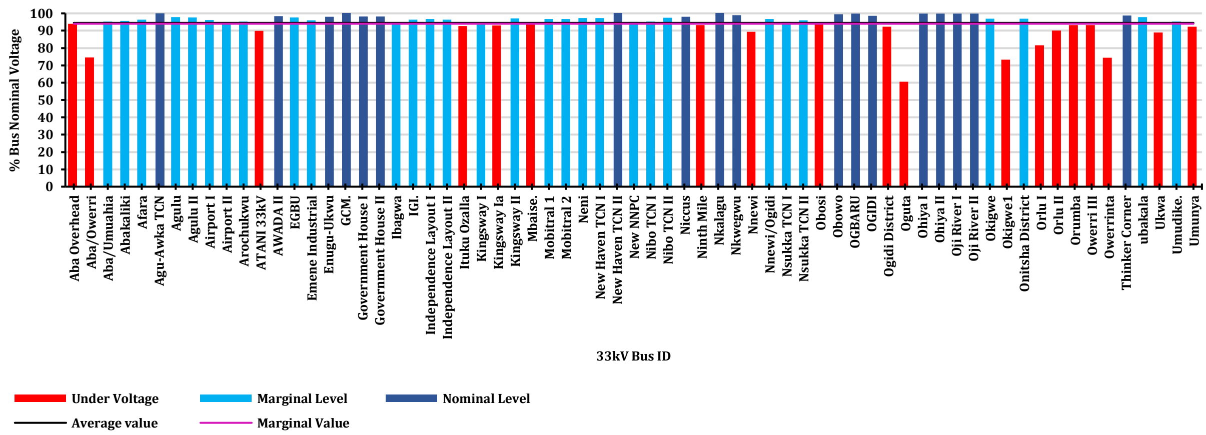

Figure 3: 33kV buses voltage profile for full load case

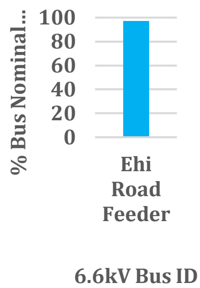

Figure 4: 6.6kV bus voltage profile for full load case

When the EEDC network is operating on full load, the results of the load flow analysis were shown in Figures 2 – 4. Figure 2 show the voltage profile of the EEDC 11 kV buses under full load operation. Forty-eight (48) out of the seventy (70) buses are operating on under-voltage. While eighteen (18) buses are operating at marginal-voltage and four (4) out of the seventy (70) buses are operating at nominal voltage in the south eastern Nigeria power system for full load operation. Figure 3, shows the 33 kV buses voltage profile in which eighteen (18) out of the sixty-seven (67) buses are operating at under-voltage. While thirty (30) buses are operating at marginal-voltage and eighteen (18) buses of the 33 kV are operating at nominal voltage level in the south eastern Nigeria power system network. Also, the 6.6kV bus (Ehi road Aba) is operating at marginal voltage as shown in Figure 4 for the 100% full load operation. According to the information contained in [9], an under voltage load shedding is efficient in increasing the level of voltage profile in every bus but not a warranty for adequate voltage stability criterion however, when the shedding of the load is carried out on 100% and lesser load operation, there is an increase in voltage stability of the network system as can be seen in the summary of the results in Table A1 and Figures A1 and A2.

3.2 When Network is Operating on 60% Load Operation - Scenario A

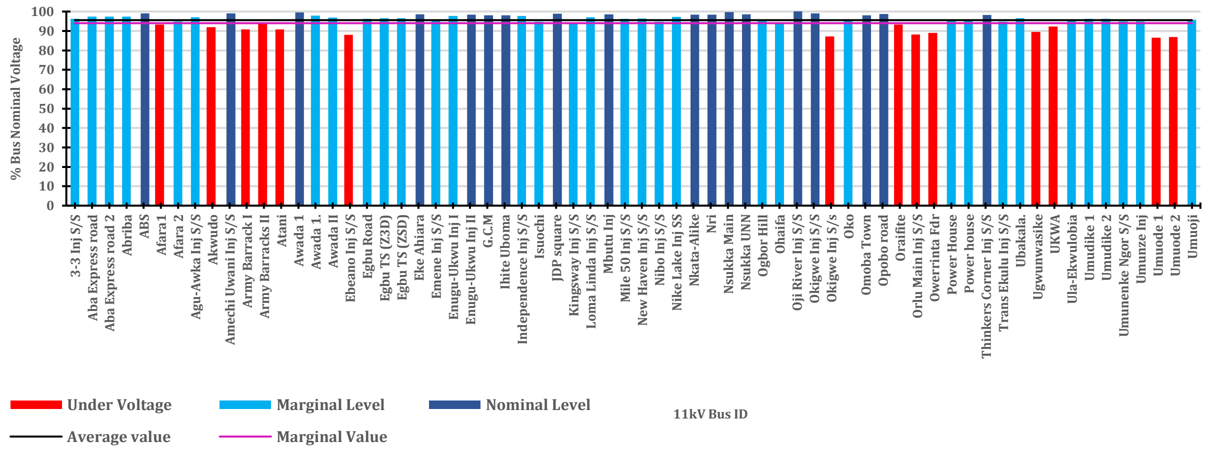

Figure 5: 11kV buses voltage profile for 60% operating load case

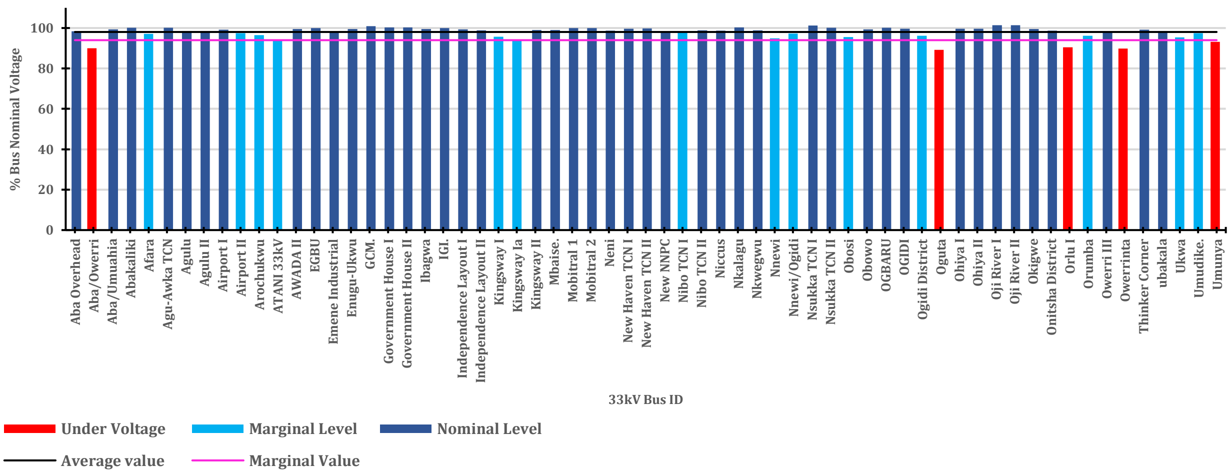

Figure 6: 33kV buses voltage profile for 60% operating load case

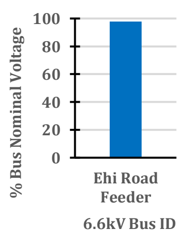

Figure 7: 6.6kV bus voltage profile for 60% operating load case

When the EEDC network has shed 40 % of its operating load for the load shedding scenario A, the results of the percentage of nominal voltage analysis were shown in Figures 5 – 7. Figure 5 shows the voltage profile of the EEDC 11 kV buses under 60% of the full load operation. Fourteen (14) of the sixty-six (66) buses are operating on under-voltage. While thirty-four (34) buses are operating at marginal-voltage and eighteen (18) out of the sixty-six (66) buses are operating at nominal voltage in the southeastern Nigeria power system for 60% load shedding scenario A operation as the load is shared among scenario A and B in the ratio of 60% to 40% respectively.

Figure 6 shows the 33 kV buses voltage profile in which five (5) out of the sixty-three (63) buses are operating at under-voltage. While fifteen (15) buses are operating at marginal-voltage and forty-four (44) buses of the 33 kV are operating at nominal voltage level in the southeastern Nigeria power system network. Also, the 6.6kV Bus (Ehi road Aba) is operating at marginal Voltage shown in Figure 7, while none of the sixty-three (63) 33kV buses is operating at overvoltage for 60% full load operation in load shedding scenario A.

3.3 When Network is Operating on 60% Load Operation - Scenario B

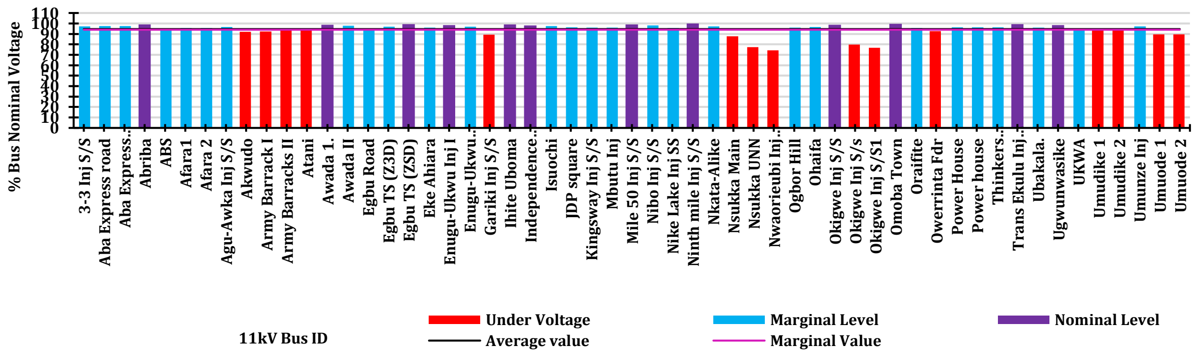

Figure 8: 11kV buses voltage profile for 60% operating load case

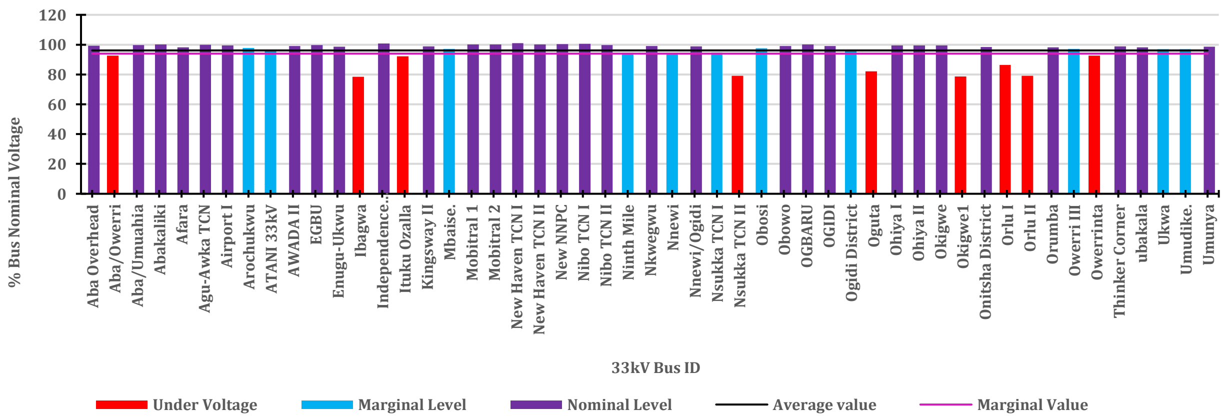

Figure 9: 33kV buses voltage profile for 60% operating load case

When the EEDC network has shed 40 % of its operating load and supplying the load shedding scenario B, the results of the percentage of nominal voltage analysis were shown in Figures 8 and 9. Figure 8 shows the voltage profile of the EEDC 11 kV buses under 60% of the full load operation. Fifteen (15) out of the fifty-six (56) buses are operating on under-voltage. While twenty-eight (28) and twelve (12) out of the fifty-six (56) buses are operating at marginal-voltage and at nominal voltage respectively in the southeastern Nigeria power system for 60% full load operation. In Figure 9, the 33 kV buses voltage profile was shown in which nine (9) out of the fifty-one (51) buses are operating at under-voltage. While eleven (11) and thirty-one (31) out of the fifty-one (51) buses are operating at marginal-voltage and at nominal voltage level in the southeastern Nigeria power system network for the 60% full load operation. Both scenarios indicate an improvement over the 100% load operation case. As reported in [10], the voltage is stable if the system maintains its voltage within acceptable limits during change in load admittance in a 3-machine 9-bus system hence better voltage stability is attained when the load is shed on 60% full load operation.

3.4 When Network is Operating on 50% Load Operation - Scenario A

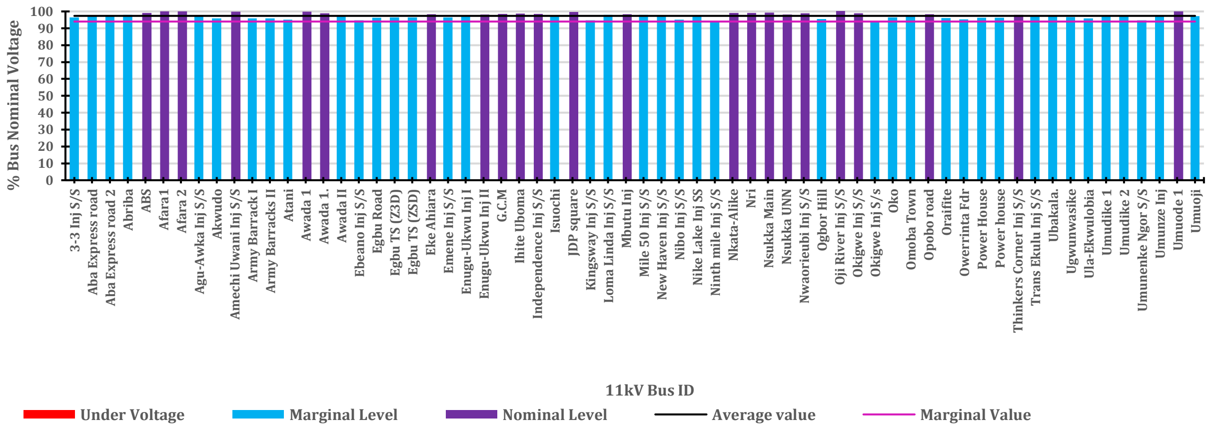

Figure 10: 11kV buses voltage profile for 50% operating load case

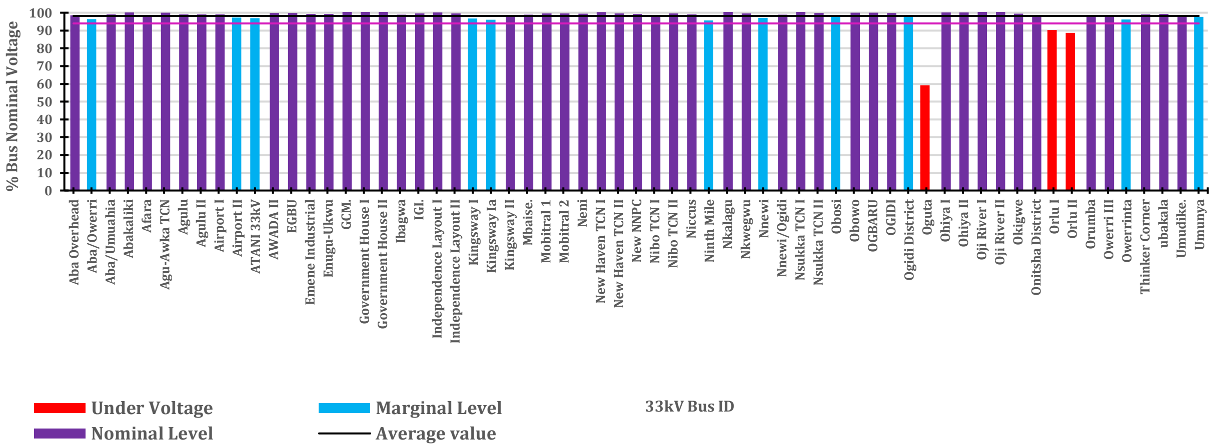

Figure 11: 33kV buses voltage profile for 50% operating load case

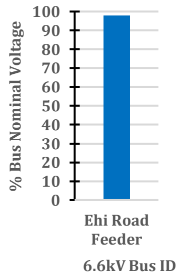

Figure 12: 6.6kV buses voltage profile for 50% operating load case

When the EEDC network has shed 50 % of its operating load for the load shedding scenario A, the results of the percentage of nominal voltage analysis were shown in Figures 10 - 12. Figure 10 shows the voltage profile of the EEDC 11 kV under 50% of the full load operation, from the result none of the sixty-four (64) buses are operating on under-voltage. While forty (40) and twenty-four (24) out of the out of the sixty-four (64) buses are operating at marginal-voltage and at nominal voltage respectively as the load is shared adequately among load shedding scenario A and B. Figure 11 shows the 33 kV buses voltage profile in which only three (3) out of the sixty-three (63) buses are operating at under-voltage. While eleven (11) and forty-nine (49) buses are operating at marginal-voltage and at nominal voltage level respectively. Also, the 6.6kV bus (Ehi road Aba) is operating at marginal voltage as shown in Figure 12, while none of the sixty-three (63) 33kV buses is operating at overvoltage for 50% full load operation in load shedding scenario A. Voltage collapse in micro grid network system [13] and conventional power network can be prevented by under-voltage load shedding when the system is shed on 50% of full load operation.

3.5 When Network is Operating on 50% Load Operation - Scenario B

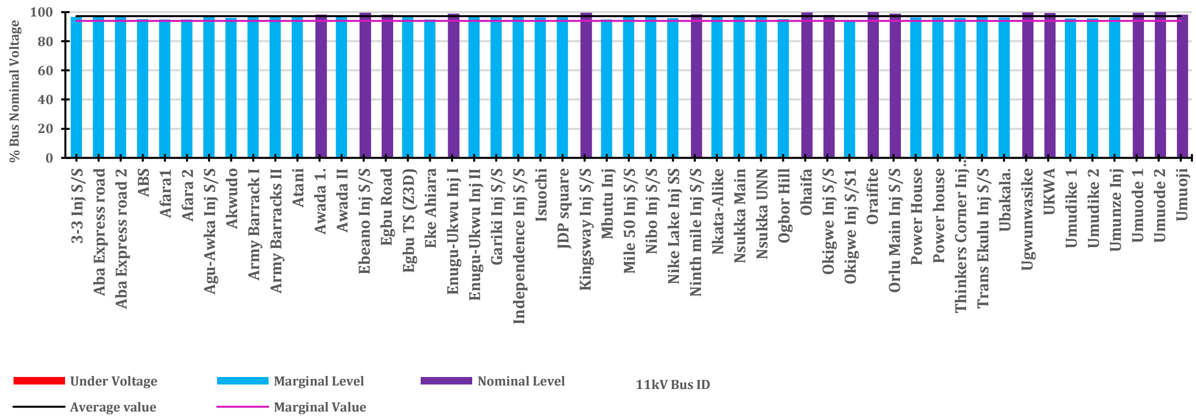

Figure 13: 11kV buses voltage profile for 50% operating load case

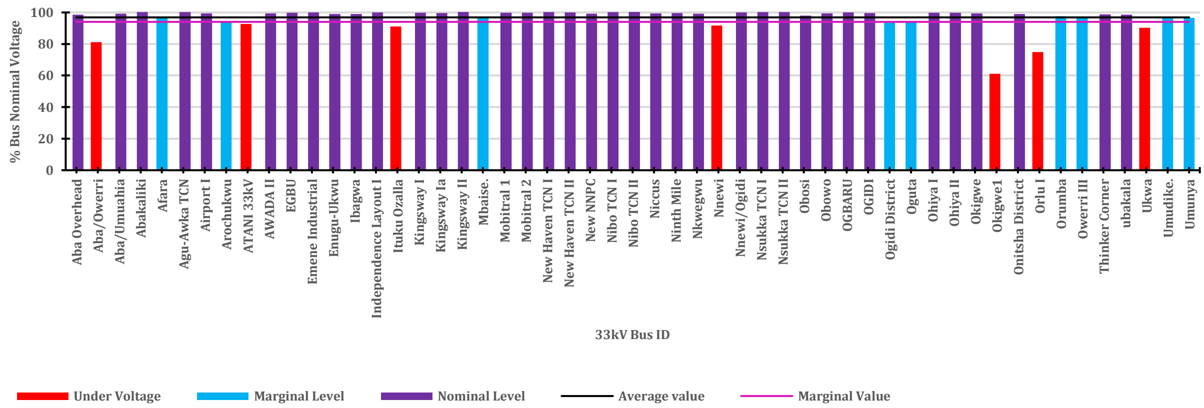

Figure 14: 33kV buses voltage profile for 50% operating load case

When the EEDC network is operating on 50 % of its operating load for the load shedding scenario B, the results of the different buses voltage profile were shown in Figures 13 and 14. Figure 13 shows the voltage profile of the EEDC 11 kV under 50% of the full load operation, from the result of the fifty-one (51) buses are operating on under-voltage. While thirty-six (36) and fifteen (15) buses are operating at marginal-voltage and at nominal voltage respectively as the load is shared adequately among load shedding scenario A and B indicating an improvement in bus voltage over the previous two load shedding cases (100% and 60%). In Figure 14, the 33 kV buses voltage profile are shown in which only and seven (7) out of the fifty-three (53) buses are operating at under-voltage. While only nine (9) out and thirty-seven (37) buses are operating at marginal-voltage and at nominal voltage level respectively. Also, none of the fifty-three (53) buses 33kV buses is operating at overvoltage for 50% full load operation in load shedding scenario B. This shows an increase in voltage level when the network is operated on 50% load shedding of 7 buses instead of analyzing load shedding scheme by the use of empirical measurement tools and load-flow simulation techniques for dynamic stability of the power system network [15].

4. Conclusion

From the simulation results of the voltage profile of the buses at each voltage level for each case study representing a given load demand level showed an improvement in the entire network bus voltage level after the load shedding scheme was applied across each case and the trend line shows an upward direction indicating an increment in the total number of nominal voltage buses of each case study, from 22 buses at 100% load demand to 105 buses when 40% of the load has been shed to finally, 126 buses when 50% of the load has been shed in the 50% load demand scenario A and B. When more load demand was shed the number of weak buses (under-voltage buses) decreases from 68 buses in 100% load demand to 19 and 24 buses in scenario A and B respectively of 60% load demand, and finally to 3 and 7 buses in scenario A and B respectively, when 50% of the total load demand has been shed by EEDC.

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Appendix

Table A1: Buses voltage level distribution for each load shedding case

CASES	% Load Demand	Operation	No of Buses		
			Under Voltage	Marginal Voltage Level	Nominal Voltage Level
CASE I	100% Load Demand	On Operation	68	49	22
CASE II	60% Load Demand	Scenario A	19	49	62
		Scenario B	24	40	43
CASE III	50% Load Demand	Scenario A	3	52	73
		Scenario B	7	45	53

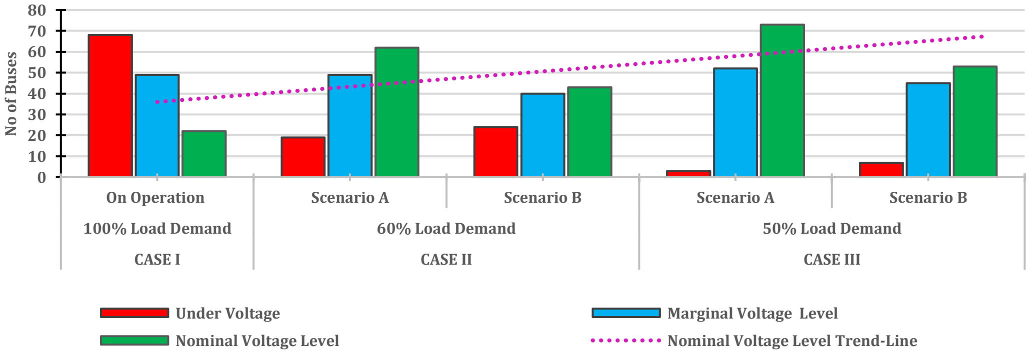

Figure A1: Number of buses voltage level for each load shedding case

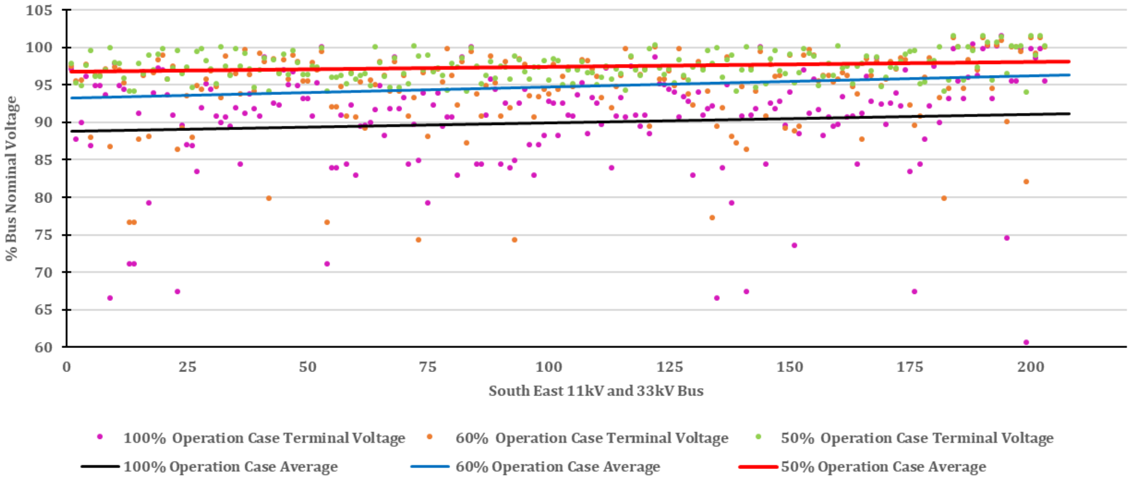

Figure A2: Voltage profile level for each load shedding case