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Research Article

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Long Variation in Voltage and Supply Interruption in a Distribution System

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Abstract
The paper examines a distribution system field data for the assessment of voltage variation and supply interruption. The under voltage has severe impacts on the consumer loads working conditions causing overloads and high transmission losses. The under-voltage limit has been set for voltage below 0.9p.u. The measurement was conducted in the control room for the duration of one week for logging interval of 1-min using Fluke VR1710 that monitors single-phase voltage quality of power network. Long duration variations are considered to be present when the limits are exceeded for greater than 1-minute time lapse. In this paper, the lowest interruption duration recorded was 20 minutes while the number of under-voltages was 41 occurrences. A simple mathematical analysis of power flow deviation was determined for correlation with the frequency disturbances recorded by the equipment. Both measurements and simulation results show that frequency rapidly changes in the network. The lowest and highest frequency vary between (48.7665 Hz to 51.196 Hz) and (48.843 Hz to 51.263 Hz) respectively. Thus, voltage and frequency disturbance statistics vindicate the voltage variation in the site to be within the ±10% limits but the overall performance of frequency monitored in the site violated the operational limits of ±0.2 Hz (i.e. 49.8 Hz to 50.2 Hz) and ±0.5 Hz (i.e. 49.5 Hz to 50.5 Hz) for the statutory regulatory. The paper would provide repository data as point of reference for Electric power sector reform act No.6 2005.

Keywords: Distribution Systems, Economic Losses, Interruption, Under-voltage, Statistical Analysis, Power Quality.

Introduction

Power quality (PQ) disturbance analyzers were used in the past as measurement equipment designed to handle only short time transient disturbances such as voltage sag and voltage swell while voltage recorders and harmonics monitors applied for steady state variations under some specific PQ events. Luckily, with advances in monitoring and processing capabilities of new instruments, extended PQ events can be obtained that reveal the full range characteristics of power quality variations in different levels of power systems [1,2]. Styvaktakis et al [3] proposed Kalman Filter techniques using a month recorded data in MV distribution systems for accurate and selective detection of voltage dip and other transient disturbances in power systems installed with static transfer switch [1-3]. The effects of capacitor switching transient, transformer saturation and fault-induced voltage dip were evaluated reporting a six-year PQ data related to interruption and voltage distortion in Norway power systems [4]. In the studied Norway network, progressive increase was recorded in the voltage distortion up to the THD of 1.7% and the interruption cost averaged to €90 million per year for outage hour of 1.7 hour per annual [4]. In another work which studied probability distribution of PQ data with special interest on the locations and occurrence time of disturbances. An Auckland real-life power data installed in over 30 monitoring sites has been surveyed by Vector Ltd since 1999 [5].

Setting objectives for determination of the reliability of measured data through real-life data; Japanesse networks were particularly monitored from 1999 to 2006 [6]. There was a detection of uncommon PQ trends with the distortion level found to be in decreasing order. It then defined a number of measuring points necessary to estimate confidence intervals evaluated to be within a ± 10% error as 50 and 120 measuring points for voltage distortion and voltage unbalance respectively Kostin and Nikitenko [7] presented statistical analysis and probability characteristics of voltage random variation on the pantograph of DC electric locomotive in the recuperation mode. The research was able to characterize the effectiveness of electric running stock voltage of the pantograph and the traction power system voltage. In the system, there were incidental running stock and traction losses with associative poor power factor. The contributions on the existing works were the analysis of statistics and probability.

A pioneering work obtained the participation coefficients of harmonic distortion in unbalanced power systems using Monte Carlo simulation techniques. The technique was based on inspection of the data involving large harmonic spectrum anchored on typical field data from California energy commission (2006), Significantly, the use of the indices along with the new variable load classes defined from real-life data makes it possible to represent several different facilities and offered a superior stratification of the simulation into hourly intervals, instead of conventional daily intervals. This new approach allows representation of the hourly deterministic components of the current waveforms [8]. de Matos et al. [9] addressed the problem of determining which non-linear loads can be considered potential harmonic sources to the voltage harmonic distortions when observed in the utility grid voltages. Statistical regression models are used to establish correlations between the simultaneously measured harmonic voltages, in the grid, and harmonic currents, at each non-linear individual load with the view to use simple low-cost PQ analyzers instead of high-tech phasor measuring devices. A lead research studied High Voltage DC (HVDC) systems to illustrate the methods of preventing commutation failures from voltage distortion caused by harmonics. It advocated for more research in the area that would buttress the strategy of limiting the DC current as the effective measures to militating against commutation failure in the systems [10].

It has been suggested that more sophisticated tools are needed to investigate issues of harmonic distortion in residential distribution networks due to the increasing penetration of multiple nonlinear loads, including modern technologies such as plug-in electric vehicles and energy efficient lighting (e.g., compact fluorescent and LED lamps) [11]. Another work established a significant difference between the values of the fundamental frequency energy and energy including harmonics and unbalance. It found out that the latter is lower than the former(i.e. the fundamental frequency active energy) [12]. The difference is attributed to the harmonic distortion energy caused by the negative power of the harmonics directed from the consumer with a non-linear load to the supply network. The findings practically confirmed the theoretical provisions on the effect of the electric power characteristics on the amount of the electric energy [12].

González-Bueno et al. [13] illustrated the higher order statistics for the detection of PQ events through the mean, variance and zero-lag third and fourth cumulants (i.e. skewness and kurtosis) techniques. The methods have been assessed to have obtained a promising overall classification rate of 99.7 % using a Feed-Forward Neural Network.

Another significant contribution proposed three individual statistics (variance, skewness, and kurtosis) and a global PQ index purposefully to improve power quality assessment and graphical representation. The approach was used to illustrate the dynamic of voltage in PQ real-life case study [14]. Another study measured the levels of voltage total harmonic distortion (THDv) in an 18-monitored site of the Alexandria Electricity Distribution Company (AEDC) with respect to both variation over time and the load characteristics of the monitored site. The analytical method adopted was to correlate the distortion disturbances with load current in the facilities. At the commercial and industrial feeders negative correlation exist between the distortion level and load current, and in the residential sites, out of eight feeders monitored and analyzed, only one of the feeders show positive correlation between the distortion indices and load current the other seven (7) are negatively correlated [15].

A recent work presents a methodology to quantify and evaluate the impact of PV integration on PQ, classified data obtained through measurement scenario approach [16]. A follow-up research investigates on nonlinear loads for individual and cumulative participations impact of the current waveform distortion in modern LV installations [17]. The work addresses several issues related to the electrical interactions between the distribution grid and different nonlinear loads, such as LED lamps, power factor correction (PFC) converters, PV inverters, and electric vehicle chargers [17].

Experimental cases on the influence of supply voltage waveform distortion for non-intentional emission in the range 2–150 kHz on common household loads such as LED lamps, CFL and induction motor as well as confirmation of the efficiency of power line communication based on selected PRIME (PoweRline Intelligent Metering Evolution) power line communication (PLC) technology have been investigated [18]. Rodríguez-Pajarón et al. [19] proposed the ANN based forecasting techniques for feeding accurate information about PQ indices to Distribution System Operators (DSO) without installing any additional monitors by relying only on the information obtained from the existing smart meters with sub-metering functionality. The results show that a reasonably small number of end-users between 5% and 20% consumers are required to have this type of smart meter in order to estimate sufficiently and accurately the THDV at LV bus bars avoiding the need to install specific PQ meters and taking advantage of the monitoring infrastructure already installed.

In view of the specialized research works presented herewith, it could be observed that the major challenge involves characterizing all the data in a convenient form so that it can be used to help identify and solve problems. Further, the PQ data is rarely monitored by the public utility companies, except through special contractual survey exercises [20]. In the older utility companies without the modern facility of distribution SCADA installation, the readings are monitored on hourly basis and the information within the dead band of one-hour is not adequately captured. This was substantiated in the study by Aliyu (1991) which had collected copious power interruption data from some selected industries in order to investigate into the effects and approximate cost impacts of electricity supply interruptions in the country [21]. It established that task of manual data was difficult such that during the survey only eight industrial consumers out of twenty-four earmarked for investigation finally supplied sufficient data deemed reliable for the study. Thus, this paper set forth to examine power quality statistics of a distribution system field data for the assessment of long variation in voltage and supply interruption for a week PQ data automatically captured within the interval of 1-min.

Materials and Method

A Simple Mathematical Analysis of Power Flow Deviations

A simple network model has been analyzed for dynamic system response in a typical power system. In power system control, system frequency and voltages are the key parameters continuously monitored to achieve desirable security and reliability of the system. The relationship between these key parameters and other dependent variables such as real (P) and reactive (Q) powers are well known in power system. The mathematical expressions are presented as follows:

Real power and reactive power are given as Equations. (1) and (2) respectively.

$$P = \frac{EV}{Z_s} sin\delta \qquad (1)$$

$$Q = \frac{EV}{Z_s} cos\delta - \frac{V^2}{Z_s} \qquad (2)$$

Where:

E is the excitation voltage in pu

V is the terminal voltage in pu

δ is the load angle in degree

Z_s is the synchronizing impedance of the transmission line in pu

A rapid change in real power is evident from (1) with the changes in load angle. Hence, the derivative of (1) gives the idea of system frequency. Conversely, the fast changes in terminal voltage will have greater influence on the reactive power more than the load angle.

Consider, a 2-bus network shown in Figure 1.

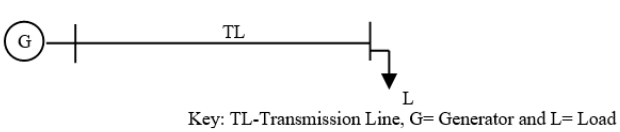

Figure 1: A 2-bus Network

The network in Fig. 1 is analyzed using MATLAB with the objective of studying the state dynamic of the system. The iterative steps adopted are as follows:

i. Carryout the initial Gauss-Seidal (G. S) Power Flow to obtain all the bus voltages
ii. Increment the system load by 20%
iii. Convert the system load to constant admittance models
iv. Form the modified network
v. Compute current injected in the load bus
vi. Determine the sudden change in the real power as a result of the 20% load increase
vii. Carryout another G.S iteration to obtain the new steady state solutions.

Expression for Interruption and Under-Voltage

The problem of long variation under prolonged interruption and under-voltage is represented by Equation (3).

$$f(t) = \begin{cases} K[u(t-t_1) - u(t-t_2)]sin\omega t \; t_2 > t_1 \\ sin\omega t \; t \leq 0 \end{cases} \qquad (3)$$

where:

sinωt is the original sinusoidal signal with nominal peak in 1 pu and ω is angular frequenc in radian per sec. K is a constant defined as 0.1≤K≤0.9 pu representing unde voltage. $u(t-t_1)$ and $u(t-t_2)$ are unit step input delayed and in Equation. (3), reproduces rectangular pulse with width between t_1 and t_2 which represents an interrupt for a time defined $t<t_1$.

Density Function of Prolonged Interruption and Under-Voltage

The density function representing prolonged interruption and under-voltage are replicated using impulse signal expressed by integral equation in Equation. (4).

$$\int_{-\infty}^{\infty} f(t)dt = 1 \qquad (4)$$

The observed characteristics of the signal, f(t) is extracted using convolution integral given in Equation. (5).

$$f(t) * \delta(t) = \int_{-\infty}^{\infty} f(\tau)\delta(t-\tau)d\tau = f(t) \qquad (5)$$

where: $\delta(t-\tau)$ is the density function.

If $f(t)$ assumes probability density function (dpf) of normal distribution, then the events under examination occur between the samples [a,b] i.e. $a \leq t \leq b$ such that Equation. (6) yields:

$$\int_a^b \frac{e^{\frac{(x-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} dx = 1 \qquad (6)$$

where:

x is sampled population observed by the recorder, μ is the average score of the sampled population, and σ is the standard deviation of the sampled population.

In order to statistically analyze the PQ data samples, an Excel code was written by Equation. (6) and results were presented.

Study Systems

The PQ data were monitored in Bauchi 132/33 kV substation continuously for seven (7) days using Fluke VR1710 connected to LV side of transformer feeding the substation equipment. Figure 2 shows the layout of the substation while Plate I is the pictorial set up of the voltage quality recorder. Extended statistical analysis was carried out on the spread sheet PQ data including normal curve fitting for each day that determine the mean, standard deviation and severity of under voltage with interruptions in the substation.

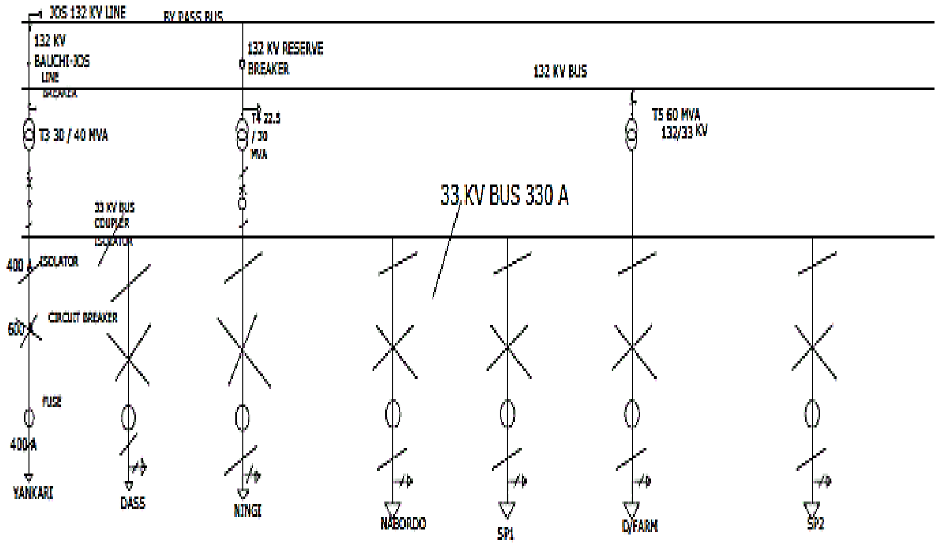

Figure 2: The Layout of Bauchi 132/33kV Substation

Plate I: *Voltage Quality Recorder (VR1710) Sources: (a) Installation Manual of Fluke VR1710 (b) Power Outlet in Bauchi)*

PQ Data

The PQ data presented has provided insight into the single phase varying of voltage in the distribution facility. Some selected results are presented in the next sections. Initially, the PQ data were acquired with the PowerLog which is the in-built firmware of the equipment. The data was processed and converted to Microsoft Excel format.

Statistical Tool

In addition to the in-built firmware that helps in retrieving the accumulated PQ data, an extended statistical tool was explored to further analyze the trends of the long duration variation within the seven (7) days measured data. This provided a convenient means of extracting required data that can reveal the severity of interruption and the trends of under-voltage variation during the measurement period.

Statistical Data

The acquired data were extracted into minimum, average and maximum values for continuous recording of key PQ data at the interval of 1-min for duration of seven (7) days. In order to achieve the set objectives of this work, the half-cycle RMS voltages were arranged into matrices of data arrays corresponding to minimum, average and maximum values within the measurement interval throughout the days and then separated into seven (7) columns with the system frequency statistically analyzed.

Results and Discussion

The section presents the actual field data acquired in the study system using simple plots and tables.

Voltage Variations

Figures 3 to 9 show the count of under-voltage variation for each day respectively. The occurrence of undesirable under voltage progressively increased in the entire period of the measurement. It is suspected that voltage regulatory control device provided for the power transformers could not take proactive actions needed for corrective measure to stabilize the supply voltage as the desirable limits. Figure 3 shows the PQ data collected in the first day between the hours of 6pm and 12 midnight. During this period, twelve (12) samples of under voltages were recorded. Similarly, the next day up to the seventh day are shown in Figs. 4 to 9 and samples kept the increasing trends which indicated reactive power balance constraint problem in the networks.

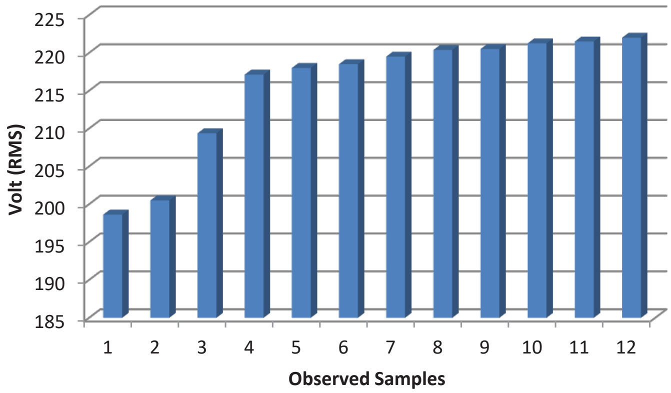

Figure 3: Frequency of Under-voltage Occurrences Day 1

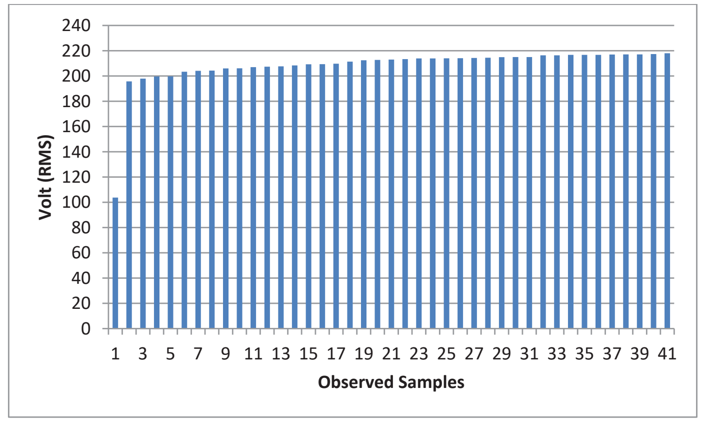

Figure 4: Frequency of Under-voltage Occurrences Day 2

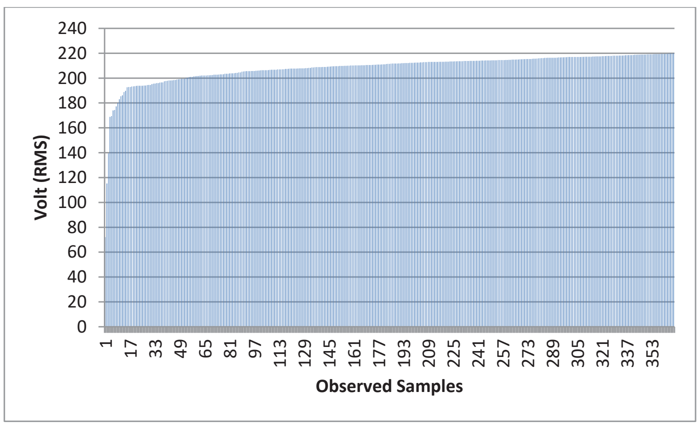

Figure 5: Frequency of Under-voltage Occurrences Day 3

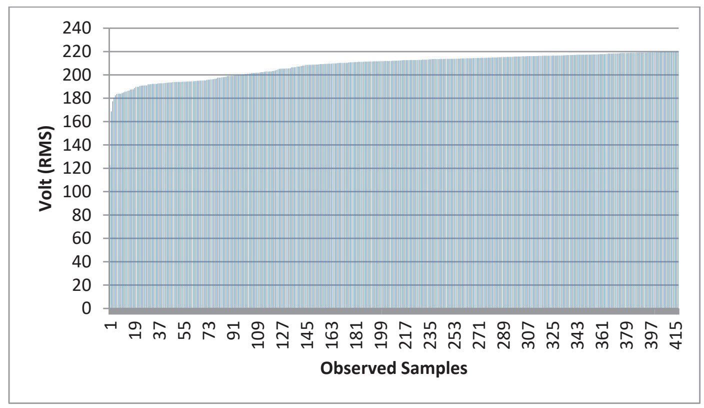

Figure 6: Frequency of Under-voltage Occurrences Day 4

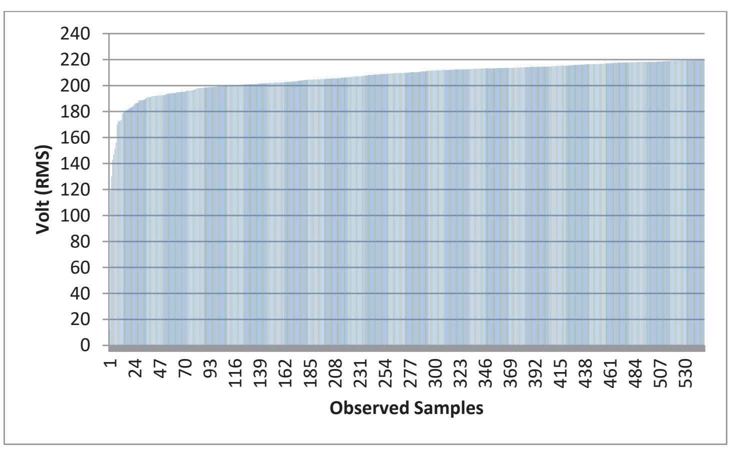

Figure 7: Frequency of Under-voltage Occurrences Day 5

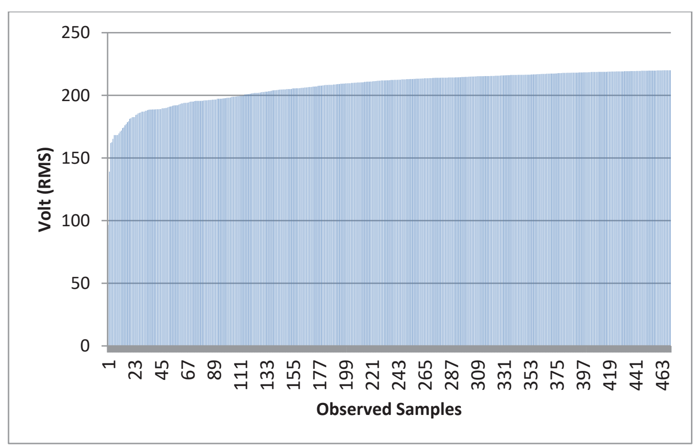

Figure 8: Minimum Voltage Sag Occurrences Day 6

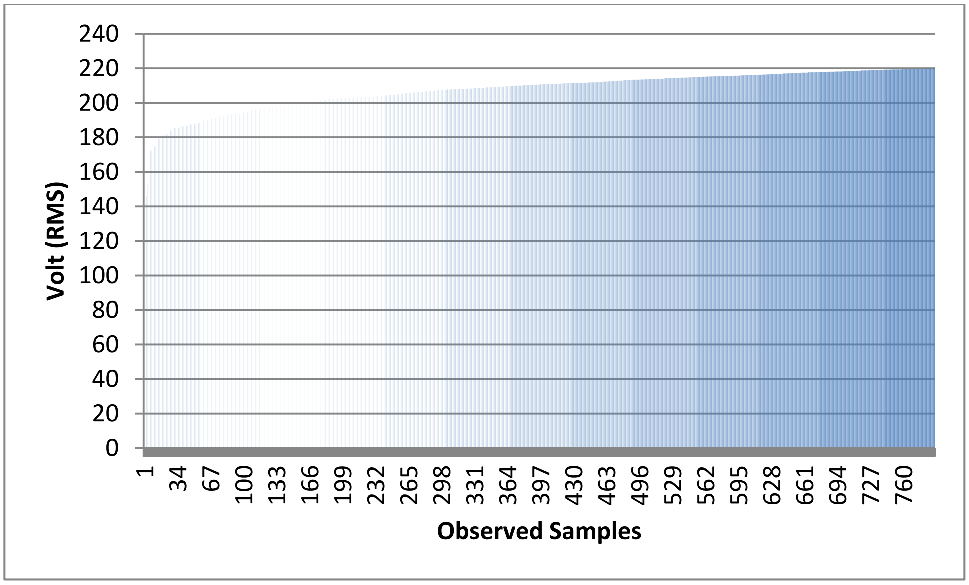

Figure 9: Frequency of Under-voltage Occurrences Day 7

Power Interruption

Some selected illustrative plots are shown for power interruptions at the monitored site from Figures 10 to 15. For sake of clarity, unlike the previous charts which purposefully focused on the number of under voltage exceeding the standard limits, the voltage-time-series plots were preferred to depict the segment of time during which the interruptions had lasted. Cursory looks at the graphs in Figure 10 revealed that were time discontinuity. These discontinuities correspond to the time interval when the power outage occurred. For instance, in Figure 11, the power was interrupted in the 0735 hours and restored back 0823 hours on third days of measurements. A simple summation of the power interruptions generated the outage data for the entire week. In a similar study by Aliyu (1991) [21] which had investigated into the effects and approximate cost impacts of electricity supply interruptions in the country. It established that outage ranged between 1hr and 6hrs as shown in Figure 16. However, the recorded interruption in the study extended up to 12hr (720mins) exact doubled this early investigation. These are shown in the plots for cumulative frequency and frequency counts as histogram in Figs 17 and 18 respectively.

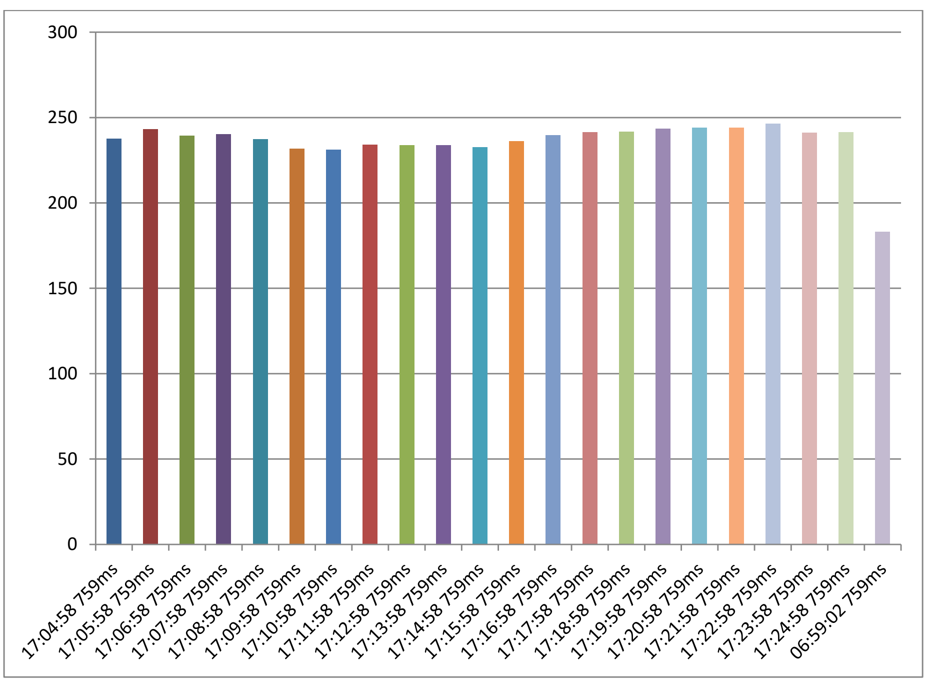

Figure 10: Segment of Voltage Time-series with interruptions on Day 2

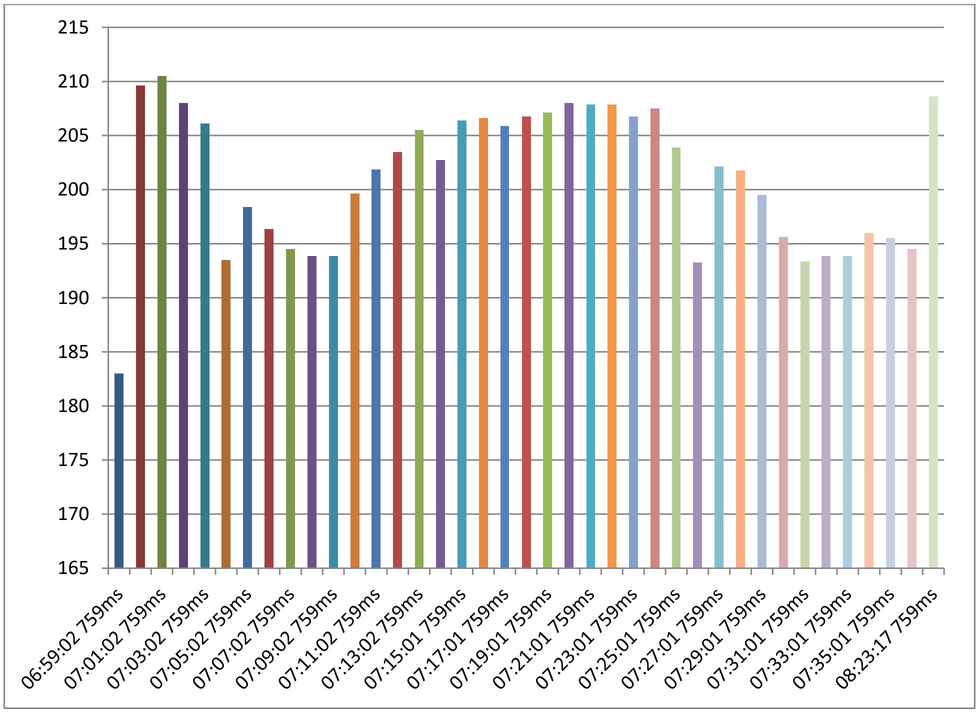

Figure 11: Segment of Voltage Time-series with interruptions on Day 3

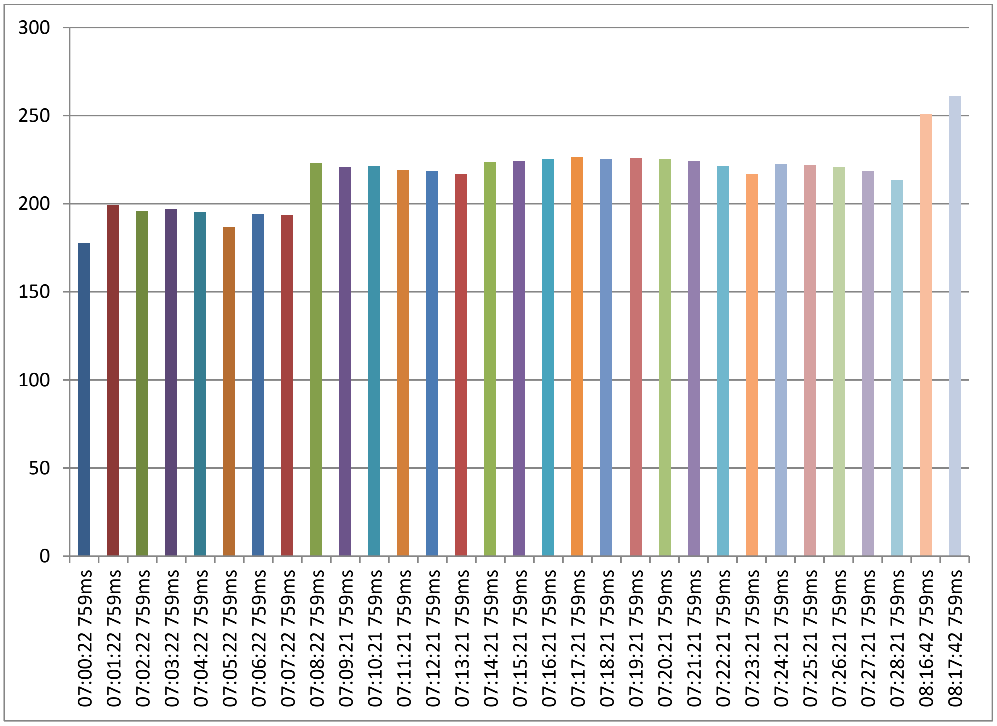

Figure 12: Segment of Voltage Time-series with interruptions on Day 4

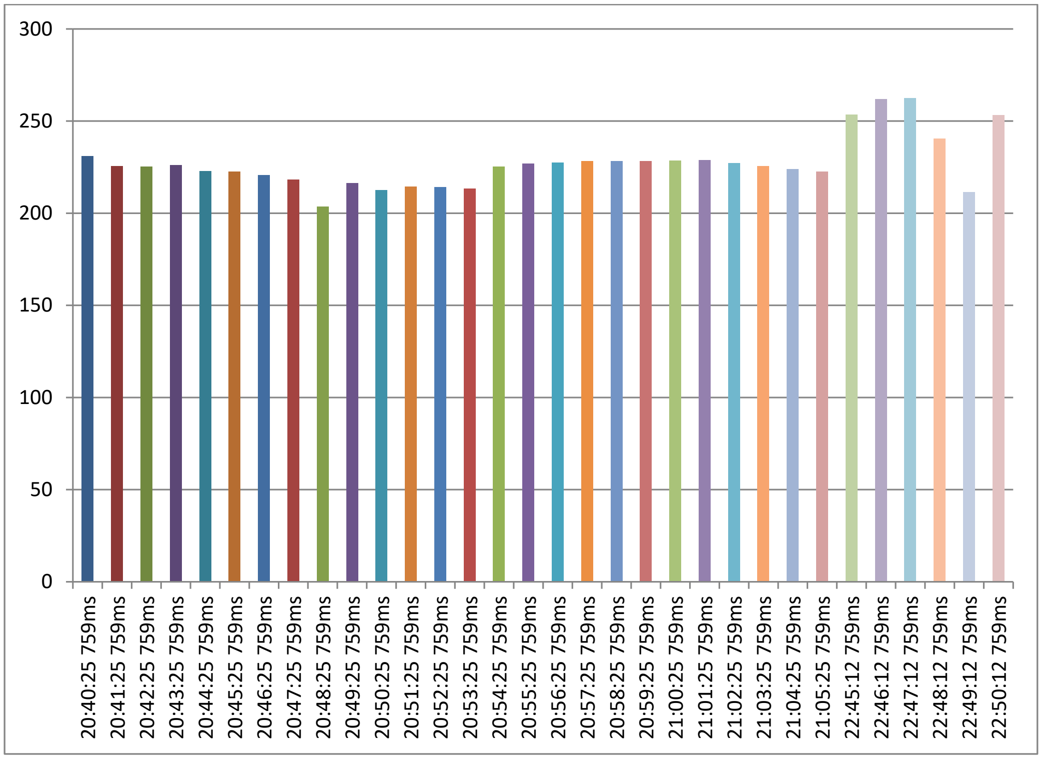

Figure 13: Segment of Voltage Time-series with interruptions on Day 4

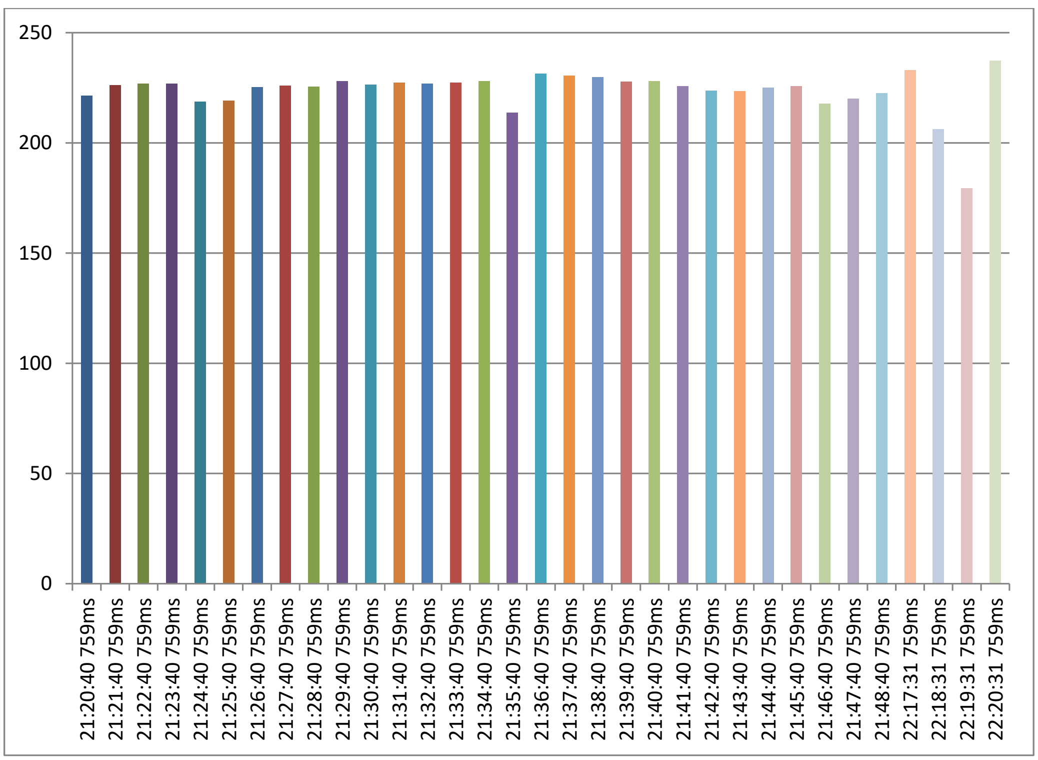

Figure 14: Segment of Voltage Time-series with interruptions on Day 5

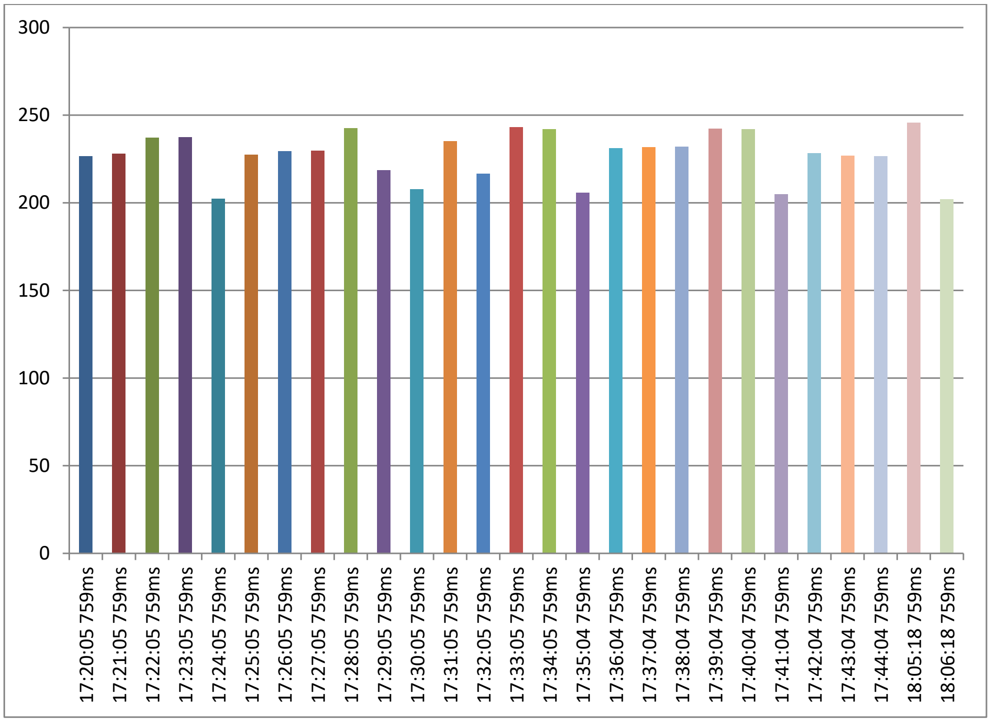

Figure 15: Segment of Voltage Time-series with interruptions on Day 6

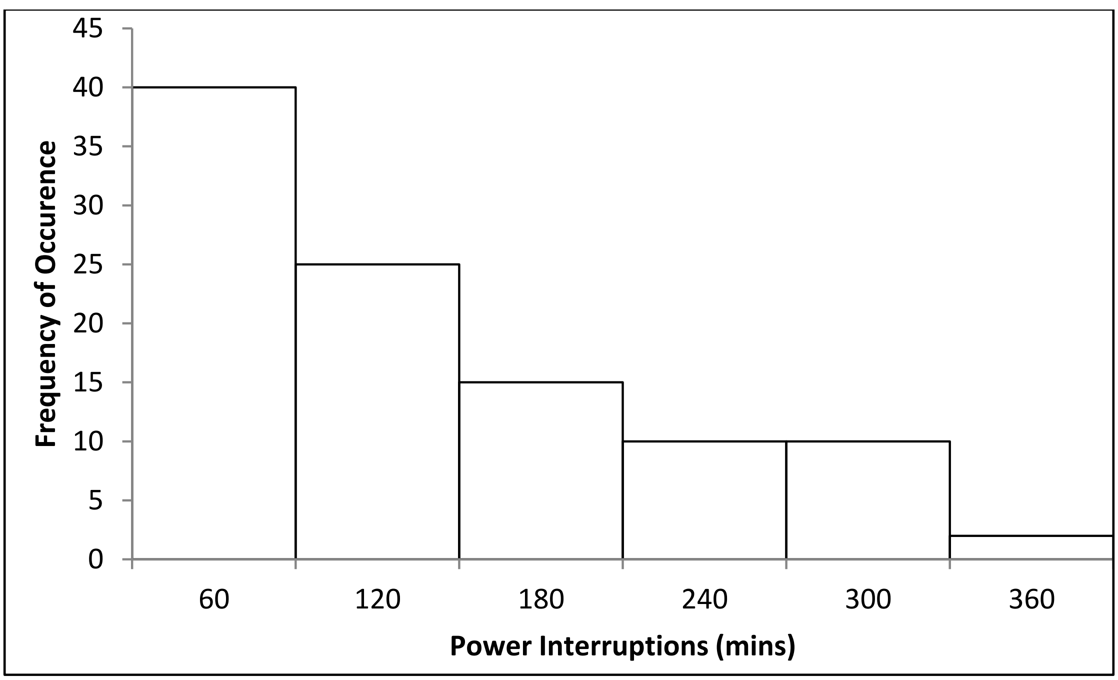

Figure 16: Frequency of Occurrence of interruptions [21]

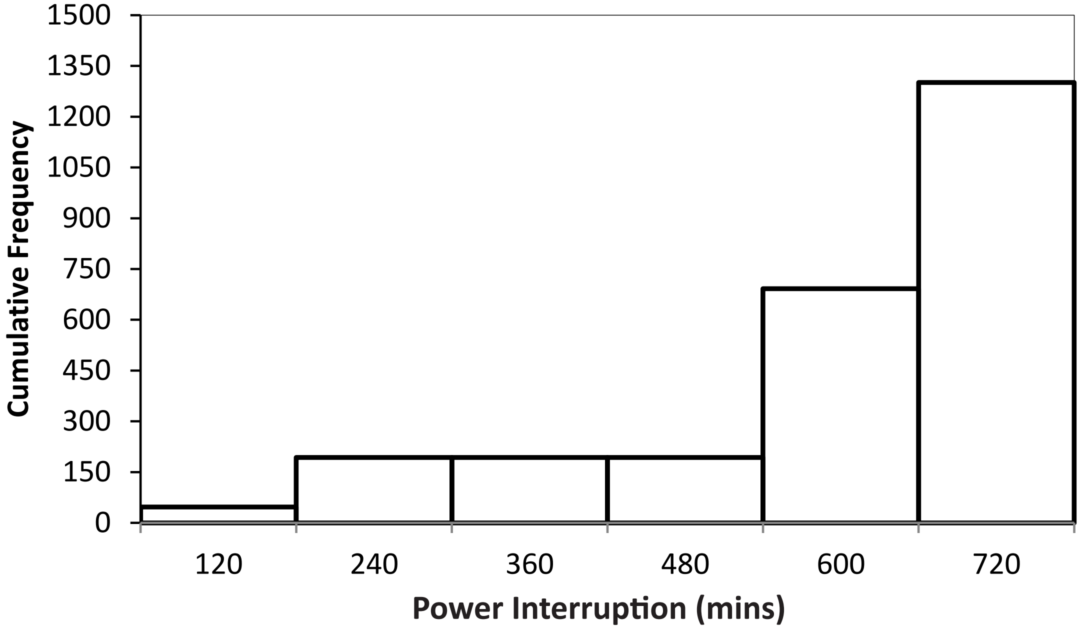

Figure 17: Cumulative Frequency of interruptions for the entire week

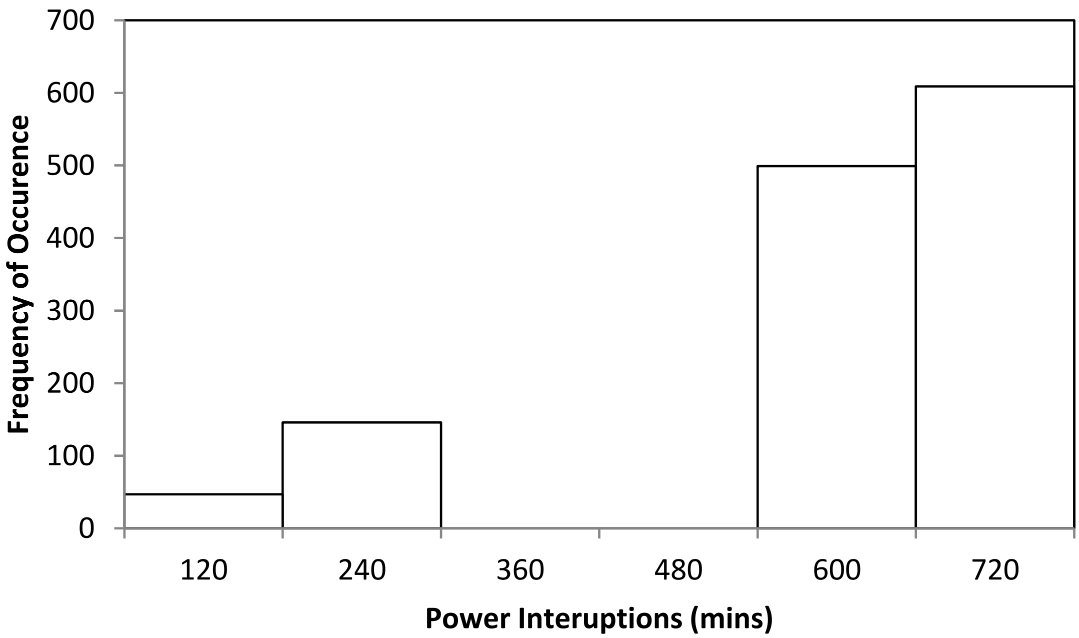

Figure 18: Frequency of Occurrence of interruptions for the entire week

Finally in the foregoing graphical results, Table 1 summarizes recorded duration of interruption in minutes and samples of under-voltage occurrences.

Table 1: PQ Statistics for Supply Interruption and Occurrence of Under-voltage

Measurement Period	Expected samples	Measurement samples	Duration of Interruption (mins)	Samples of under-voltages
Day 1	353	353	0	7
Day 2	1440	831	609	41
Day 3	1440	941	499	361
Day 4	1440	1294	146	401
Day 5	1440	1413	27	541
Day 6	1440	1420	20	451
Day 7	1440	1440	0	761
Total	8993	7692	1301	2563

From Table 1, it is observed that the severity of supply interruption stood at 1301 minutes (i.e. nearly one day of outage) and the under-voltage occurred in increasing orders except for day 6 where there were lesser cases of under-voltage than the preceding day 5. There are other days with relatively high supply availability, noticeably, the first day and the last day even though the PQ recorder started in the third quarter of the day and in the last day, the supply was perfectly for 100% availability. However, the under-voltage occurrence was the highest. There was cumulative distribution of under-voltage occurrence of 761. Both interruption and under-voltage durations violated the recommended standards ANSI C84.1 1989 which specifies the steady state voltage tolerances for both magnitudes and unbalance expected on a power system. Long duration variations are considered to be present when the limits are exceeded for greater than 1-minute time lapse. Confidentially, the sample recorder time interval was 1 min. The interruption cumulatively occurred in 1301 mins and the under-voltage has 761 cases which could be translated to 761 minutes of incessant dip in the system voltage.

Power Flow Deviation

The results of power flow deviation are shown in Figs. 19 to 21. Fig. 19 indicates that the system frequency drops to 0.045pu Hz during the sudden changes in the power and the swing equation together some proportional-integral differential (PID) controllers (details not shown) regulate it back to near nominal. There is a steady state error indicating the difficulty in achieving the nominal frequency of 50 Hz absolutely. This is also shown in the swing equation dynamic plot for the 20% load increase as in Fig. 20. The measured PQ data captured the system frequency so as to indicate the frequency disturbances of the substation. The changes in frequency give the real power transition constraints such that input power equates the sum of load demand plus the losses. When load increases beyond the input power the frequency drops and vice versa. A similar response was obtained in the case of voltage deviation in Fig. 21. It could be observed that the impact is not too pronounced in way to provide the reactive power transition in the network.

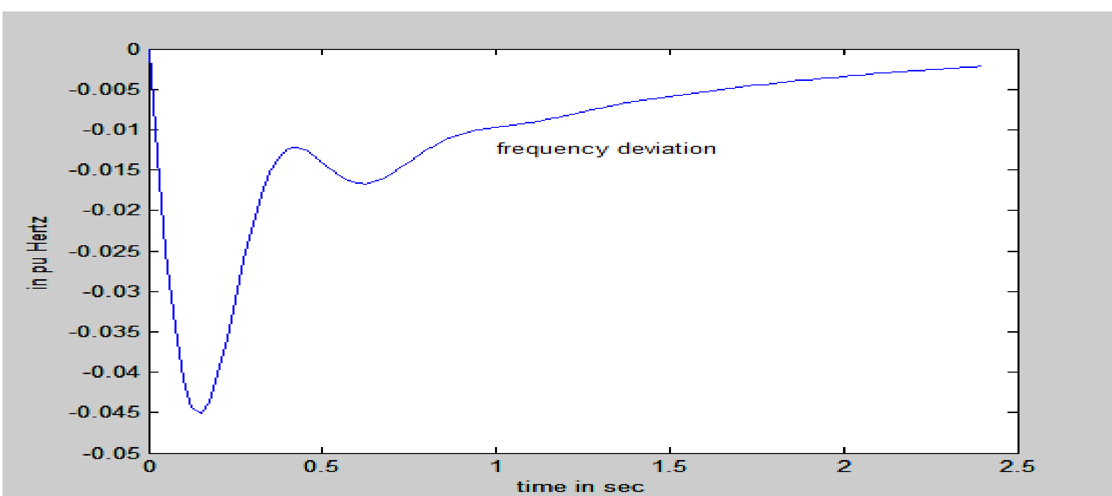

Figure 19: Simulation of Frequency Deviation in a network

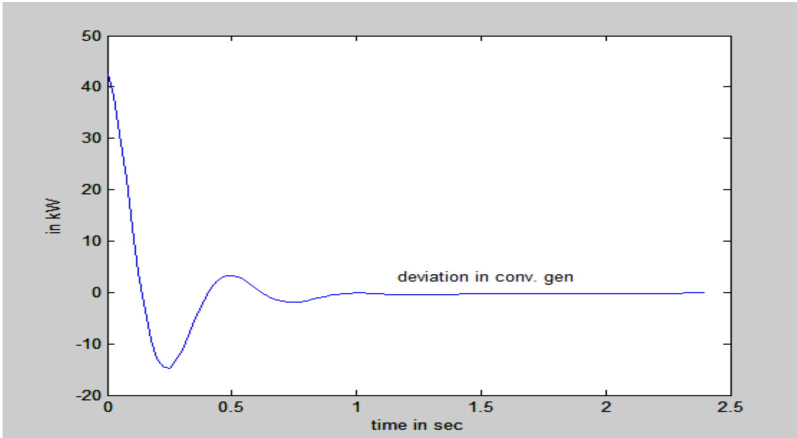

Figure 20: Simulation of Swing Equation transition in a network

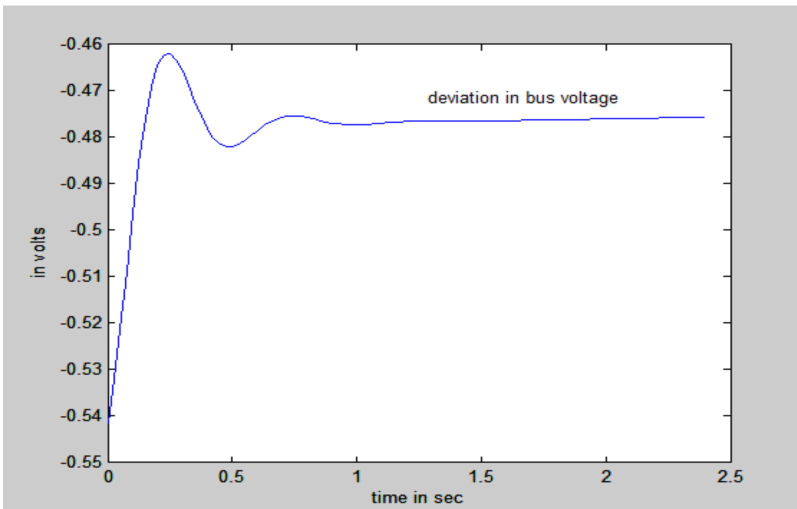

Figure 21: Simulation of Voltage Deviation in a network

Normal Distribution Curve

The PQ data was fitted into Gaussian normal distributions and statistical indices of the trends were determined. Figures 22 to 23 show the fitting plots of the distribution based on the recorded data.

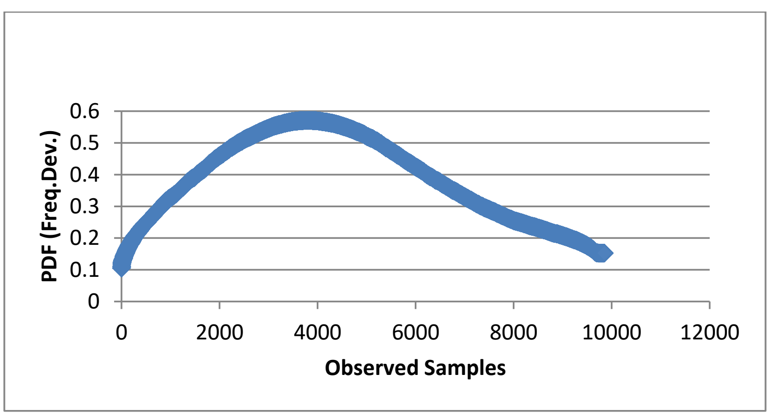

Figure 22: Normal Plot for Supply Frequency Statistics

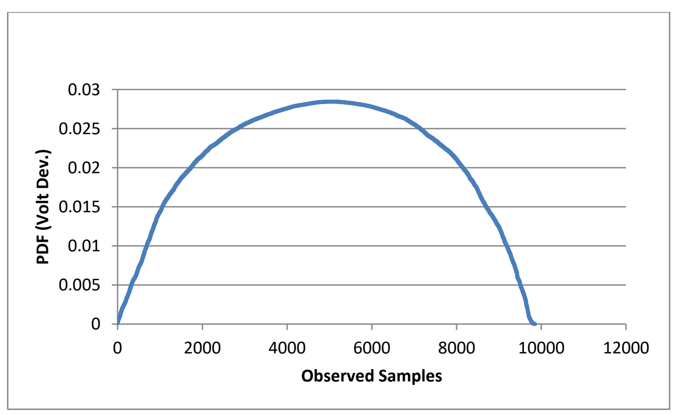

Figure 23: Plot of Normal Curve of Under-Voltage with Maximum recorded voltage

Table 2: Voltage Variations

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
	Measured Voltage in volt	Measured Voltage in volt	Measured Voltage in volt	Measured Voltage in volt	Measured Voltage in volt	Measured Voltage in volt	Measured Voltage in volt
Min.	198.63	103.75	75.13	122.75	12.13	96.63	86.13
Mean	240.65	235.96	222.54	223.74	221.13	222.97	247
Max.	256.75	278.88	270.75	262.38	256	253.13	247

Table 3: Frequency Disturbances

Supply Frequency (Hz)				Supply Frequency (Hz) (maximum)			
Min.	Mean	Max.	Std Dev	Min.	Mean	Max.	Std Dev
48.7665	50.12823	51.196	0.698675	48.843	50.32653	51.263	0.646213

Tables 2 and 3 comprise voltage variation and system frequency disturbances respectively. The minimum, mean and standard deviation were extracted from the recorded data. The average value of single-phase voltage for the lowest and highest recorded data were obtained as 12.13 V and 278.88 V respectively. By validation of the voltage recorded, according to IEC and European EN 5016, the voltage tolerance limits are kept within ±10%, so the recorded data presented in Table 2 confirmed globally that voltages are within tolerable limits determined to be 9.49 V and 14.02 V.

The mean values of the lowest and highest recorded system frequency were found to be 50.13 Hz and 50.32 Hz respectively. The frequency disturbances revealed changes in the lowest and highest frequency between (48.7665 Hz to 51.196 Hz) and (48.843 Hz to 51.263 Hz) respectively. Thus, the overall performance of frequency violated the operational limits of ±0.2 Hz (i.e. 49.8 Hz to 50.2 Hz) and ±0.5 Hz (i.e. 49.5 Hz to 50.5 Hz) for the statutory regulatory limits. This is observed as presented for both minimum and maximum frequency in Table 3. The implication of this variation is that there are rapid load following requirements in the power network and the active power balance transition constraints are usurped. At the lowest frequency, the loading level of the system would be excessively high while at the highest frequency the loading level would be low.

Conclusion

The research has demonstrated the severity of interruption and under-voltage at the indoor control point of power reticulation of the 132 kV/33 kV substation. This paper has provided repository data statistically shown for both interruption and under-voltage durations. The recorded data violated the recommended standards ANSIC84.1 1989 which specifies the steady state voltage tolerances for both magnitudes and unbalance expected on a power system should not exceed 1min duration lapses. It has been shown that the interruption cumulatively occurred for 1301 mins and the under-voltage has 761 cases (i.e. 761 minutes) of incessant dip in the system voltage. There are currently three unbundled entities; it is most likely envisaged that the mitigating improvements would have been applied under new competitive energy of non-regulated GENCOs and DISCOs energy systems. This work is considered as point of references for the new owners under the Electric power sector reform act No.6 2005. It is therefore recommended that the measurement should be conducted frequently to protect the power system from the adverse effects of interruptions and under-voltage at various key load centres of the study system.

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