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*Original Article*

# Development of Sinusoidal Regression Model for Voltage Deviation Evaluation in the Power Quality Assessment of Ado-Ekiti Metropolis

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***Abstract*** - *Power Quality (PQ) modeling and evaluation is very important in recent times due to complexity in the grid network and this was based on the injection of non-linear devices and continuous introduction of renewable energy sources (RES) into the existing networks. The continuous introduction of RES and non-linear devices such as inverters, uninterruptible power supplies has contributed to power quality index such as short, medium, long interruptions, voltage dips, flickers, voltage swells, spikes, and harmonics among others. This paper reviewed the indices of PQ. Measurements were carried out with the aid of multimeter for certain areas of Ado-Ekiti metropolis for a period of 24 hours in aweek. A linear and nonlinear model was developed based on voltage deviation output of straight line and sine trend which are -0.00667 T +0.21 and0.13-0.04 sin 30(T-12) as a function of time of 0 to 11:59 and 12:00 to 24:00 respectively. The result shows that the maximum deviation of 0.21%occurs at 0:00 and decreases as it tends toward noon, while from noon the deviation is in sinusoidal format ranging at 0.09% to 0.17%.*

**Keywords** - *Evaluation, Network Model, Power, Quality, Regression.*

## I. INTRODUCTION

Power Quality index are voltage sags, harmonics, voltage swells, voltage interruptions, voltage fluctuations, under-voltage, over-voltage, voltage notching. Transients which will be described as itemized in this paper. Power Quality issues have not been handled seriously in the time past because the loads on the network were linear in nature. However, with the growth in population and developments in electronics, non-linear loads are now injected into the networks and this has changed the behavioral pattern of the system (Olulope and Adeoye 2018). The issues with PQ are numerous and will be reviewed sequentially

## II. REVIEW OF LITERATURES OF PQ INDEX

### *A. Voltage Sags*

These are usually caused by system faults. It is a decrease of the normal voltage level between 10 % and 90 % of the nominal root mean square voltage at power frequency for duration of 0.5 cycle to 1 minute(Masoum& Fuchs, 2015). Researchers have used various approaches to assess voltage sags in the past such as voltage drop equation, secant method, failure risk method, contours of voltage performance, system average R.M.S variations Frequency Index; Fuzzy model for risk assessment model, analytic and probabilistic methods; time sequential Monte Carlos simulation; voltage sag prediction based on voltage divider model and direct calculation of time domain, steady state solutions for systems containing non-linearity and electronically switched loads, error analysis of numerical integration methods used in time domain simulations (Hong et al., 2011); (Kishore et al., 2014); (Lehtonen, 2016); (Yun & Kim, 2003); (Goswami et al., 2009);(Sagre et al., 2016); (Ezhiljenekkha & Marsalinebeno, 2020).

### *B. Harmonics*

These are alternating current voltage and current integral multiples of the supply fundamental frequency. It is obvious that odd harmonics are present or in existence when harmonics and fundamental frequency are added together, this results in single distorted waveform. Harmonics are produced when non-linear loads such as un-interruptible power supply, inverters, variable drives like arc furnace, welding machines, voltage controller and frequency converter (Johnson & Hassan, 2016) are used. Harmonics lead to degradation of motor insulation due to heat generated by it in the conductor and energy waste in electrical system.Another factor that negatively impacts the power quality comes from the presence of modern power electronics technology as the output interface of power plants. These devices not only produce harmonics in the system, but are also very sensitive to distorted voltage signal. Passive filters are designed for different applications. Current sub-harmonics and inter-harmonics generated by cycloconverter need to be attenuated by filtering. IEEE-519 defines the limits for odd and even harmonics but not for inter-harmonics whereas IEC -61000-2-4 sets the voltage harmonic limits for industrial plants with voltage levels up to 35 kV and just provides guidelines for treating inter-harmonicsSeveral indices are available for harmonic analysis; however, the two most commonly used are the total harmonic distortion (THD) and the total demand distortion (TDD)(Benali et al., 2018)(Ceyhun et al., 2015)(Yaghoobi et al., 2019);(Sagre et al., 2016).

### *C. Voltage Swells*

Switching over-voltage incidents in industries can cause insulation degradation(Alkasasbeh& Almaita, 2017). It is the antonyms of voltage sag which is simply momentary increase in nominal voltage. It rises within 1.1 to 1.8 per unit of the nominal voltage for duration of half a cycle to several seconds. It is usually set up when heavy loads is switched off, loss of generation, badly regulated transformer, faulty conditions at various points in the distribution system, underloading of a phase while the remaining two phases are overloaded(Johnson & Hassan, 2016).

### *D. Voltage Interruption*

This is sub-divided into very short and long interruptions. Very short interruption is the total interruption of electrical supply for duration from few milli-seconds to one or two seconds. It is mainly caused due to the opening and automatic reclosure of protection devices to a faulty section of the network(Benali et al., 2018) (Khan et al., 2016). For long interruption, it is the total interruption of electrical supply for duration greater than one to two seconds. This is caused by failure of equipment in the power system network, storms and objects striking lines or poles, fire, human error, bad coordination or failure of protection devices (Farhoodnea et al., 2013).

Voltage fluctuation: It is the oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 50 Hz. It is caused by arc furnace, frequent start / stop of electric motors, oscillating loads(Abas, 2020).

### *E. Voltage fluctuation*

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### *F. Under-Voltage*

This is a decrease in nominal voltage to less than 0.9 per unit in more than one minute duration. It is caused by switching of large load, circuit overloading and line faults(Johnson & Hassan, 2016).

### *G. Over-Voltage*

Temporary over-voltages are abnormal disturbances at the power frequency that occur under the usual operating conditions of a distribution system. These are caused by system faults and open neutral connection(Luo et al., 2016).

### *H. Voltage notching*

Notches can be created in the supply voltage when large power electronic drives in adjacent loads cause a momentary short-circuit between the phases that power the drive, each in turn. These are called commutation notches and occasional cause some interference with each other loads that use the 50 / 60 Hz power frequency as a controlling signal. Notches are considered as a special case of harmonic emission and the remedies, if interference is noted and are similar to those of harmonics(Masoum& Fuchs, 2015).

### *I. Voltage Unbalance*

It is voltage variation in a three phase system in which the three voltage magnitudes or the phase angle differences between the voltage magnitudes or phase angle differences between them are not equal. It is caused by large single phase loads such as furnace, traction load, incorrect distribution of all single-phase loads by the three phase of the system (Gaunt, 2014).

**Table 1. Power Quality Parameters and their Mitigation Techniques**

| S/N | Power Quality Parameters | Mitigating Techniques |
|---|---|---|
| 1. | Voltage sags | Installation of protective devices in between process and grid. Constant Voltage Transformer, Dynamic Voltage Restorer, Uninterruptible Power Supplies, Static Compensators, Flywheels |
| 2. | Harmonics | Passive or Active arrangement, Passive Series line reactor, tuned filter, induction filter, resonance filter, Active shunt filter, hybrid filter |
| 3. | Voltage swells | Installation of protecting devices in between process and grid. Constant Voltage Transformer, Dynamic Voltage Restorer, Uninterruptible Power Supplies, Static Compensators, Flywheels |
| 4. | Voltage interruptions | Using energy storage system at the point of common connection, uninterruptible power supplies |

| | | |
|---|---|---|
| 5. | Under-voltage conditions | Shunt capacitors, shunt reactor, SVC, STATCOM, tap changing of transformer. |
| 6. | Over-voltage conditions | Shunt capacitor, shunt reactor, SVC, STATCOM, tap changing of transformer |
| 7. | Voltage fluctuations | Dynamic voltage regulator, synchronous machines, STACOM |
| 8. | Voltage notching | Series connections of impedance reactor with source |

Source: (Mallajoshula & Naidu, 2019).

**Table 2. Power Quality Modeling of Ado-Ekiti Metropolis using Linear Regression model**

| **Day (D)** | **Time T (hr)** | $V_{dev1}$ | $V_{dev2}$ | $V_{dev3}$ | $V_{dev4}$ |
|---|---|---|---|---|---|
| **196** | **6** | **0.1707** | **0.1707** | **-0.083** | **0.3333** |
| **197** | **9** | **0.1594** | **0.6** | **0.0213** | **0.2308** |
| **198** | **12** | **0.1483** | **0.8462** | **0.0573** | **0.2632** |
| **199** | **15** | **0.0909** | **0.0434** | **0.0213** | **0.1163** |
| **200** | **18** | **0.1429** | **0.0909** | **0.0345** | **0.2632** |
| **201** | **21** | **0.1707** | **0.0435** | **0.1538** | **0.1009** |
| **202** | **24** | **0.1163** | **0** | **0.1163** | **0.0909** |
| **203** | **6** | **0.1429** | **0.0667** | **0.1429** | **0.2** |

**Source: Olulope and Adeoye, 2018**

## III. METHODOLOGY

This paper reviewed the indices of power quality issues and the mitigation techniques. Measurements were carried out with the aid of ar6 circutor power quality meter for certain areas of Ado-Ekiti metropolis for a period of 24 hours in a week. A linear and nonlinear model was developed based on voltage deviation output of straight line and sine trend, which are -0.00667 T +0.21 and 0.13-0.04 sin 30(T-12) as a function of time of 0 to 11:59 and 12:00 to 24:00 respectively. The result shows that the maximum deviation of 0.21% occurs at 0:00 and decreases as it tends toward noon, while from noon the deviation is in sinusoidal format ranging at 0.09% to 0.17%.

### *A. Fourier's formula for 2π-periodic functions using sines and cosines*

Periodic function of $f(x)$ that is integral for [−π, π] with the application of equation 1 and 2 were use in establishing the fourier series model as given by Bird, (2002) and Oladebeye & Ejiko, (2007; 2015a).

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos(nx)\partial x \quad , n \geq 0 \qquad (1)$$

and

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin(nx)\partial x \quad , n \geq 1 \qquad (2)$$

are called the Fourier coefficients of $f$. One introduces the partial sums of the Fourier series for $f$, often denoted by $(SnF)$ =

$$\frac{a_0}{2} + \sum_{n=1}^{N}\left[a_n \cos(nx) + b_n \sin(nx)\right] , N \geq 0.$$

The partial sums for $f$ are trigonometric polynomial. One expects that the function $(SnF)$ approximate the function $f$, and that the approximation improves as N tends to infinity. The infinite sum

$$\frac{a_0}{2} + \sum_{n=1}^{N}\left[a_n \cos(nx) + b_n \sin(nx)\right]$$

is called the Fourier series of $f$. The condition n≥1 are called the Fourier coefficients

where $\frac{a_0}{2}$ serves as the amplitude function of A as given by Ejiko et al. (2019) with the application of equation 4 and 5 as given by Ejiko et al, (2015b; 2020)

$A=\frac{b+d}{2}$ (3)

b= $minimum\ point$

d= $maximum\ point$

$A=\frac{0.09+0.17}{2}=0.13$

$a_n$ serves as the function of negative and positive quantity above the mid-point.

Again, $a_n=\frac{b-d}{2}=\frac{0.09-0.17}{2}=-0.04$

F(x)=sin(nx) for a period of $2\pi$; because n cycles is $360^0$

12 hours (n)= $2\pi$ because cycles is $360^0$.

12 n= $2\pi$,

$n=\frac{2\pi}{12}$

$$V_d=\frac{b+d}{2}+\frac{b-d}{2}\sum_{x=1-12}^{\theta=\infty}\sin\left(\frac{2\pi}{12}\right)x \quad (4)$$

$$V_d=0.13-0.04\sum_{x=0-12}^{\theta=\infty}\sin 30x \quad (5)$$

$$V_d=0.13-0.04sin30(T-12) \quad (6)$$

y = mx + c (7)

where $m=\frac{\Delta Y}{\Delta X}=\frac{y_2-y_1}{x_2-x_1}=\frac{0.17-0.13}{12-6}=0.006670.$

$$0.17=0.00667(6)+c \quad (8)$$

where x= 6. y= 0.17 and c is unknown

$0.17=-0.00667(6)+c$

c = 0.17 + 0.04 = 0.21

Therefore,

$$y=0.00667+0.21 \quad (9)$$

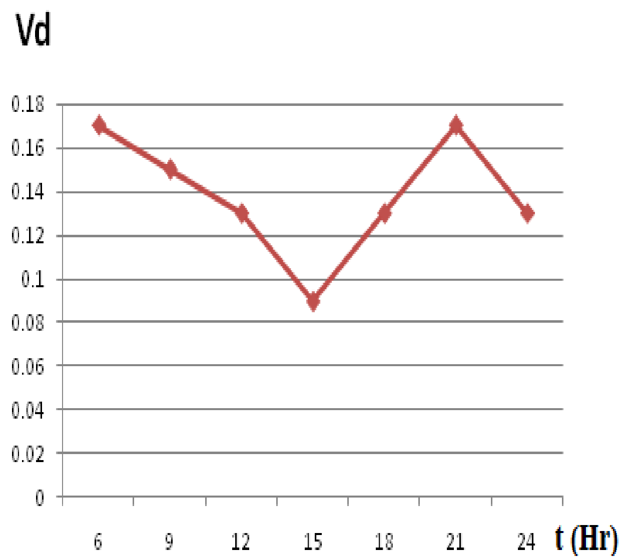


**Fig. 1 Regression and Sinusoidal Trend of Voltage Deviation**

## IV. RESULTS AND DISCUSSION

The paper extensively reviewed power quality issues and their mitigating techniques as enumerated in Table 1. Table 2 is the power quality model of Ado-Ekiti metropolis with the use of linear regression model whose output was defective from the 15 to 24 hours and needs improvement that led to the application of sinusoidal model. The graph in Fig. 1 shows sinusoidal regression model for voltage deviation evaluation in the Power Quality Assessment of Ado-Ekiti Metropolis. The sinusoidal regression model was developed from Fourier series equations of steps of equations 1 to 5 to establish equation 6. The behavior of the sinusoidal regression model when the time was 6, 9, 12, 15,18, 21 and 24 hours were 0.17, 0.15, 0.13, 0.09, 0.13, 0.17 and 0.13 respectively. The voltage deviation from 6:00 hrs to 12:00 hrs is of linear trend, hence the derived equation 9 is of simple regression model. The daily voltage deviation is maximum about 6:00 hrs and 21:00 hrs where majority of the homes are expected to be making use of their electrical appliances. The deviation is minimal at 15:00 hrs during afternoon break and 24:00 hrs and beyond when most occupants are asleep.

## V. CONCLUSION

The paper carried out sinusoidal regression model of Ado-Ekiti metropolis. The paper was able to contribute to knowledge by correctly changing the non-sinusoidal behavioral pattern of power quality of Ado-Ekiti to sinusoidal wave through the implementation of the model.

## RECOMMENDATIONS

Based on the results that worked in consonance with the objective, the following recommendations were made:

(1.) Further research should be carried out with the view of injecting different solar PV penetrations and possibly other renewable energies.

(2.) The time for future research should be extended to months.

(3.) Real time simulations should be carried out with sophisticated power quality meters.

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