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Original Article

Non-Linear Loads and K-Factor Analysis on Power Distribution Transformers (Case Study: Lagos State, Nigeria)

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Abstract *- The novel innovation in technology has introduced a large percentage of non-linear loads in electricity networks. The impact can no longer be ignored due to their influence on power quality. Non-linear loads are known to draw distortion currents that generate harmonics, which causes overheating in transformers and often shortens the life span of the transformers and increases maintenance costs. This work examines the influence of non-linear load on distribution transformers by using two 500KVA,11kV-415V distribution substations as a case study. Table 7 shows the harmonics currents data captured at two substations, and the computed Individual Harmonic Distortion (IHD) and Total Harmonics Distortion (THD) for 9 a.m. data collected are reflected in Table 15 for both IEEE and IEC methods. The result shows that the THDs are 34.9% (IEEE) and 32.6% (IEC) for substation A and 56.4% (IEEE) and 48.3% (IEC) for substation B. According to ANSI/IEEEC57.110, any transformer with THD above 5% needs to be de-rated. Also, the K-factor for transformer de-rating computed, shown in Table 16, for the two substations' transformers, using IEEE methods, reveal a K-factor of 12.89 and 21.69 for substation A and substation B, respectively, while the IEC method values are 11.073 and 17.24 respectively. The need to de-rate the substation transformers for protection and increase the life cycle cannot be over-emphasized.*

Keywords *- Power quality, Non-linear loads, Power distribution transformer, Harmonics, K-factor.*

1. Introduction

The world advancement in technology-driven engines is electricity; aside from the fact that electricity has become the basis for economic development, the standard of living, and the rate of national growth of a country, the visibility of the involvement of electricity in the Key Performance Indices (KPIS) use in measuring a nation economic growth is easily seen in the way nations increases their electricity generating capacity virtually every year.

Table 1 shows the generating capacity of the listed countries in five years interval. A look at China and America will explain why they are taking the lead in world trade, especially China. Electricity growth, however, comes with associated challenges. Apart from the greenhouse effect resulting from some of its modes of generation, there are also notable losses associated with its consumption. Electricity operational losses are seen at the three major levels, viz-a-viz generation and transmission and distribution levels. The distribution level is our focus as per this evaluation. At the distribution level of electricity, transformers play a crucial role in linking the consumer to the power supply system. The various consumer loads connected at this level can be classified as linear and non-linear loads. Linear loads are identified as loads with a Power Factor (PF) of unity, while non-linear load has a power factor less than 1. Aside from this classification, non-linear load current characteristics do not mimic (or follow) the same fundamental waveform as that of the supplied voltage.

This distorted current drawn by non-linear loads generate harmonics that cause several overheating in the transformer, which often shortens the life span of transformers and increases maintenance costs. K- Factor is a Key index for evaluating the impact of non-linear loads on a distribution transformer and as well as formulating a regulation for transformer rating. These are captured in ANSI-IEEE C57.10 and IEEE standard C57.12.10.2012 standards. The Quest to improve the standard of living, boost economic growth, and automate daily tasks through Artificial Intelligence (AI) and Internet Of Things (IoT) trends has placed high demand and absolute dependence on electricity. This has resulted in a continual increase in the nation's electricity-generating capacity over the years, as documented in Table 1.

Table 1. Generation capacity in five years interval (GIGAWATT) - GW

Country	1980	1985	1990	1995	2000	2005	2010	2015	2020
China	65.871	87.054	137.891	218.712	323.526	518.511	970.896	1518.608	2224.791
USA	577.614	653.252	720.781	753.614	811.719	978.019	1039.062	1073.833	1143.266
South Africa	20.548	24.369	33.853	37.76	46.253	42.14	46.309	47.18266	62.727
Ghana	1.06	1.185	1.187	1.187	1.17	1.754	2.608	3.8664	5.3494
Nigeria	2.507	4.192	5.958	5.881	5.893	5.905	8.5752	10.597	11.6912
France	63.416	86.311	103.228	107.429	114.722	116.504	125.0675	133.598	138.2576

Source: International Energy Agency (IEA) 2023 (iea.org/energy-system/electricity)

2. Electrical Loads and Harmonics

Electricity Generation increase, however comes with associated challenges. Apart from the greenhouse effect resulting from some of its modes of generation, there are also notable losses associated with its consumption. While some losses are normal, others are abnormal. The abnormal losses are caused by technological advancement that brought in some loads classified as non-linear loads.

Normal Losses – are caused by linear loads
Abnormal Losses – are caused by non-linear loads.

2.1. Linear and Non-Linear Loads

The electricity utility (Grid concept) system was designed with the assumption that loads are electro-mechanical – Voltage and Current waves are sinusoidal, or loads will be linear. However, advancement in technology has brought in different kinds of loads that now influence the initial design concept and affect power generation parameters' quality. The proliferation of these new loads initiates the need for load classifications into what we regarded as Linear loads (the originally intended load) and non-linear loads (the emanating loads associated with advancement in technology). According to Michades et al. (2021), the increase of new technologies in recent times and the changing of conventional appliances to power electronic–driven appliances can be observed in residential and commercial buildings feeding from Low Voltage (LV) distribution networks, these are the advent of non-linear loads that causes significant deterioration in power quality.

2.1.1. Linear Loads

Linear loads are simply AC electrical loads whose voltage and current waveforms are sinusoidal, and the current at any time is proportional to voltage. Linear Loads include power factor improvement capacitors, filament lamps, heaters, etc. Figure 1 shows the voltage and current waveform of a typical linear load via a harmonic analyzer.

2.1.2. Non-Linear Loads

Non-linear loads are AC loads where the current is not proportional to the voltage, and their waveforms are distorted and no longer sinusoidal. The nature of non-linear loads is to generate harmonics in the current waveform which distort the current waveform. This distortion in the current waveform leads to distortion of the voltage waveform and causes the current waveform to be no longer proportional to the voltage waveform. Non-linear loads include computers, rectifiers, printers, television sets, power electronic equipment, etc. Figure 2 shows a simple illustration of the voltage and current waveforms of a non-linear load.

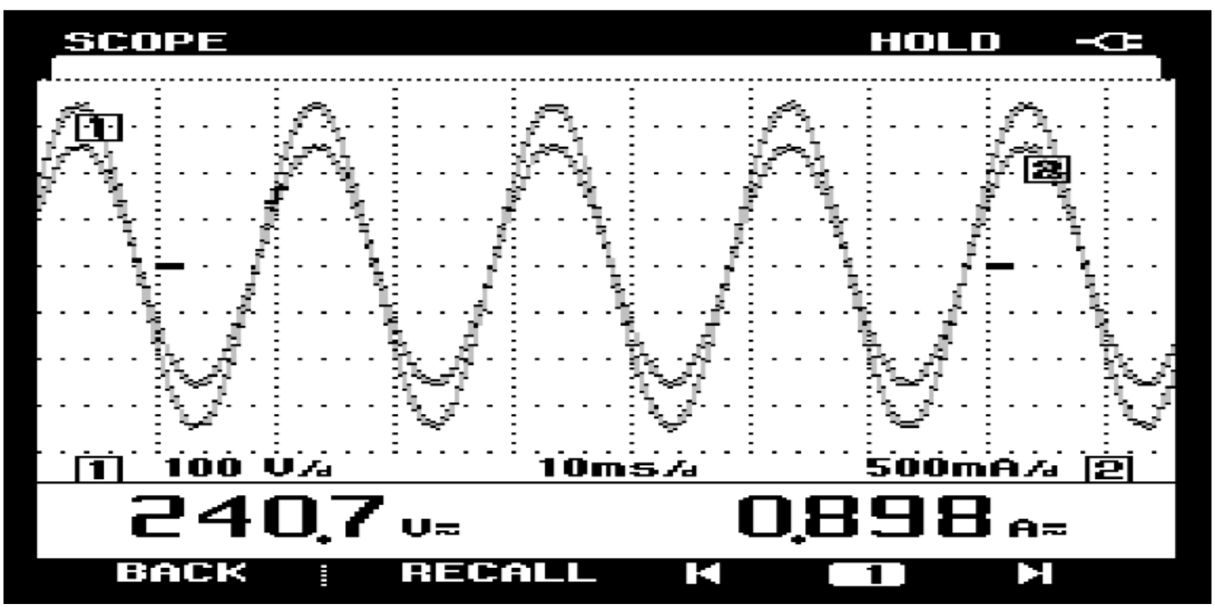

Fig. 1 Voltage and current waveforms of a typical linear load

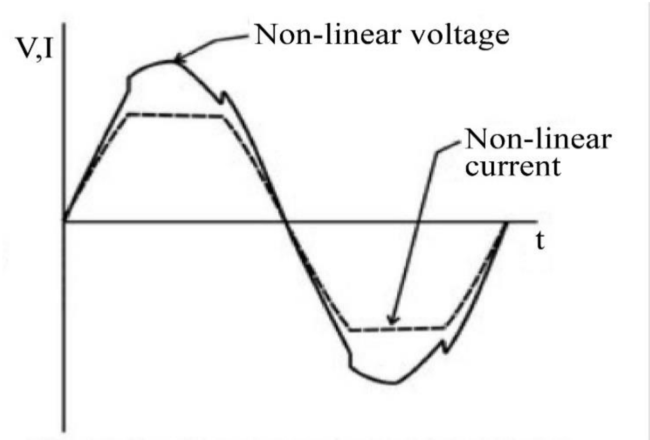

Fig. 2 Voltage and current waveforms of a typical non-linear load

Table 2. Linear and non-linear load's major differences

	LINEAR LOAD	NON-LINEAR LOAD
Ohms law	Ohm's laws is applicable	Ohm's law is not applicable
Crest factor	Crest factor = 1peak/1RMS =√2 =1.41	The crest factor could be 3 to 4
Power factor	Power factor = watts/(V × I) = COSØ	Power factor=watts/(V × I) = COSØ = displacement factor × distortion factor
Harmonics	The load current does not contain harmonics.	Load current contains all ODD harmonics.
Load category	It could be inductive or capacitive	It cannot be categorized as a leading or lagging load
Load type	Resistive, inductive or capacitive	Usually, equipment with a Diode and capacitor
Neutral current	Zero neutral currents if 1 Phase, loads are equally balanced on 3Phase mains	Neutral current could be 2.7 times the line current even if 1Ph, loads are equally balanced on 3Ph. Mains
Inrush current	May not demand a high inrush current while starting	Essentially, a very high inrush current (20 times normal) is drawn while starting for approximately one circle.

SOURCE: Electrical -knowhow.com (2023)

2.2. Non-Linear Load Historical Trend

Generally, power systems operate at a specified frequency peculiar to the country's grid frequency of operation. Major and popular grid frequencies are 50Hz and 60Hz. In Nigeria, the grid frequency is 50Hz, while that of the United States is 69Hz. The 50Hz and 60Hz are regarded as fundamental frequencies. According to Prof. Grady (2012), certain load types generate currents and voltages whose frequencies are integer multiples of these fundamental frequencies. These higher frequencies are known to be the major cause of electrical pollution (or distortion), referred to as power system harmonics. Harmonics in power systems is an old phenomenon that, as early as 1916, publication on the third harmonic caused by iron saturation in transformers and machines was made by Steinmatz. Steinmatz proposed Delta connections for blocking third harmonic currents in three three-phase systems. The Steinmatz approach to solving the harmonics problem was very effective till the 1930s and 40s when telephones and electrical circuits were placed on the common right of way. At this period, the harmonic currents produced by transformers and rectifiers in the power system are coupled inductively into the open-wire telephone circuit adjacent to it and generate audible telephone interference. This second stage of the harmonics problem was minimized using a filter circuit and a reduction in the magnetizing current of the transformer core. Further improvement was achieved by replacing the open-wire telephone circuit with a twisted pair, fiber optics and buried cable. The quest to minimize harmonics continues as modern technologies continue to introduce non-linear loads which are grossly embedded in electronics devices and switching power supplies. Nitin Kumar et al. (2015), an Electricity utility (grid concept) system, was designed at the onset with the assumption that loads are electro-mechanical, or voltage and current waveforms will be sinusoidal, and loads will be linear.

The assumption was due to the types of loads existing at the early stage of grid network design, construction and operations, which were largely linear loads. However, as technology grows, in recent years, harmonic in power systems has increased substantially due to a rapid increase in non-linear loads. According to Fluke Incorporation (2023) in their paper 'Quick guide to power quality symptoms and causes', an untrained eye may not see or recognize the associated problems with the electrical distribution network or the connected equipment as a product of power quality problems because no immediate problem is apparent. Hence, such problems might be written off as just an old breaker which needs replacement or as a one-time nuisance reset. Some wave patterns associated with power quality problems are shown in Figure 3.

2.3. Voltage and Current Harmonics Source

The concept of pure sinusoidal waveform not having distorted harmonics or nil harmonics distortion is hypothetical and not practically possible. At the generation, the output voltage waveform contains a trace of distortion caused by the field excitation non-uniformity and the discrete distribution nature of the stator coils of the generator in their slots. This distortion in the generation output is typically less than 1.0% and is thus regarded as insignificant.

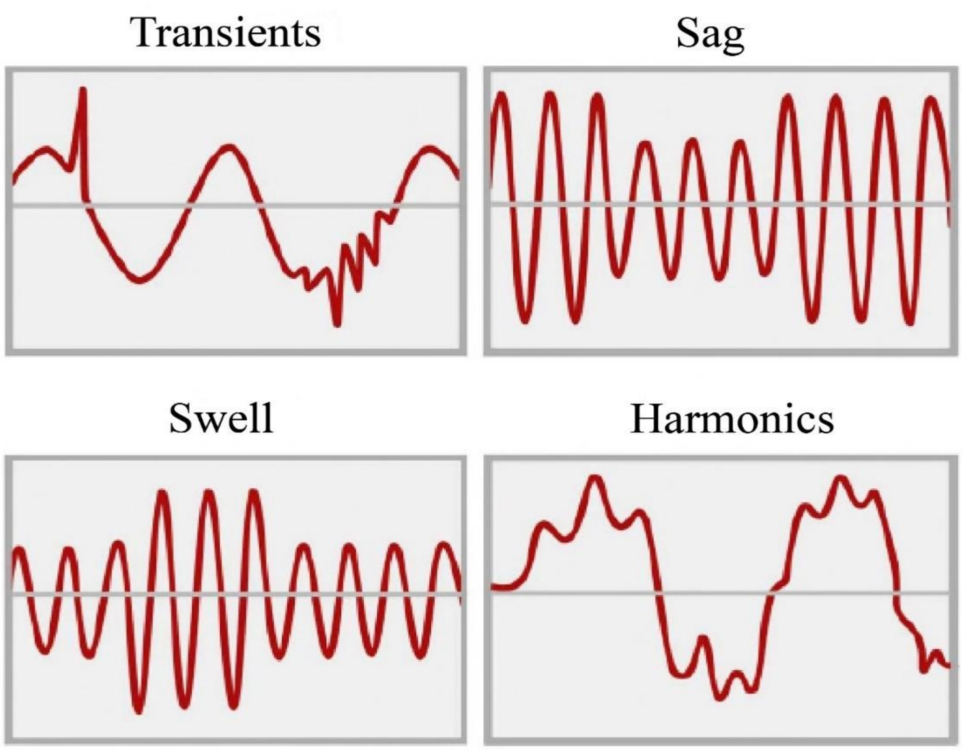

Fig. 3 Some power quality parameters waveforms (Source: Fluke Instrument)

The voltage distortion at the generation part of the power system network produces harmonics that travel several miles via the transmission and distribution networks until they finally get to the power consumers. The consumers' loads are substantially non-linear. Hence, currents drawn are rich in harmonic frequency components, especially in industrial installations and large commercial complexes. These harmonic or distorted currents flowing in the power system network, caused by the non-linear loads, further increase voltage distortion, influenced by impedance voltages of various power distribution equipment (like cables, buses, line conductors, transformers, etc.). Hence, the non-linear loads flowing in the power system produce voltage distortions that increase gradually from the generation source towards the load points due to the circuit impedances. The consequence of this is that a significantly distorted supply voltage will cause even linear loads to generate non-linear currents. Also, several categories of consumers on a grid network do share a common line, and this causes the voltage distortion produced by the current harmonics injection of one consumer to significantly affect other consumers. To minimize the effect of harmonics, standards are developed to regulate harmonic contents respective electric power consumers can inject into the power system. According to Silva (2019), the major power equipment causing harmonics include computer and data-processing loads, adjustable speed drives, fluorescent lighting, arc furnaces, rectifier banks, etc. The way to limit this is to carry out harmonics analysis of the distribution substations to determine environments with the production of appreciable harmonic frequencies spectrum that is sent to other loads to cause undesirable results in the system, which is the basis for this research.

2.4. Relationship Between Harmonics and Power Quality in Power Supply System

The power quality problems are grouped broadly into two; which are voltage anomalies and harmonic distortion. In the groupings, it is clearly seen that harmonic is a subset of power quality or one of the problems in power quality. According to Khalid and Dwiredi (2011), parameters that describe power quality include:

i. Voltage sags
ii. Voltage variations
iii. Interruptions swell
iv. Brown-outs
v. Black-outs
vi. Voltage imbalance
vii. Notching
viii. Noise, Ground noise
ix. Crest factor
x. Impulse
xi. Voltage spikes
xii. Drop out
xiii. Flicker
xiv. Harmonics distortion, Harmonic resonance and Inter-harmonics
xv. Transient, etc.

The complexities in the power system today are the consequences of:

a. Society is becoming increasingly dependent on electrical supply
b. New equipment, which are more sensitive to power quality variations
c. The advent of modern power electronic equipment

Power problems cannot all be eliminated. However, the anomalies can be corrected before they do damage if the symptoms can be spotted earlier. Darioush et al. (2023) consider the fact that there are two major power quality problems to be focused on, which are voltage unbalance and harmonics disturbance, thus making harmonics issues a major one in solving power quality problems. Khan et al (2017), in recent days, power quality is now very complex for both electrical power utilities and power system engineers. The power distribution equipment is now highly responsive to disturbances that arise in power systems, and these result in harmonics distortion which causes inefficiency in power usage and abrupt failure of equipment. This consequently affects the production process in industries and causes financial losses, also causing a reduction in power generation and data processing is not left out. According to Khalid and Dwivadi (2011), major ongoing work by IEEE in the development of harmonic standards is focused on modifying standards 519-1992. 519-1992 standard for the regulation of harmonics in Power Systems networks set limits on current and voltage harmonics at the Point of Common Coupling (PCC) or metering terminal. This is to ascertain that the electricity utility company will

1. Deliver acceptable clean power with standard quality to all consumers.
2. Protects electrical equipment within its network from excessive harmonic overheating and prevents loss of life. Hence, 3% and 5% limits are set, respectively, for Individual Harmonic Distortion (IHD) and Total Harmonic Distortion (THD).

Distortion limits are set at 25% for odd harmonics and I_{SC}/I_L < 20 distortion base limit for all electric power generation equipment, where I_{SC} represents the maximum short circuit current at the Point of Coupling (PCC) and I_L is the maximum fundamental frequency load current at PCC for 15 or 30 minutes duration. Here in the study, we will limit our discussion to Harmonic distortion and later extend it to distribution transformers, which is our project focus.

2.5. Review of Harmonic Distortion in Power System

Harmonics are known to cause voltage and current distortion in power systems, which consequently not only affects power system parameters quality but also harms system equipment. Anicetus and Kusmadi (2014), Harmonics are known to cause transformer failure and they cause temperature rise in transformers and decrease in efficiency. This is possible because the major effect of harmonics is the increase in system current. In particular, the increase in neutral conductor current is due to the sharp increase in zero sequence current caused by the third harmonic. According to Samira Nasar et al. (2020), non-linear loads and devices in a power system are known to cause harmonic distortion in system current and voltage. The distorted current and voltage waveforms are decomposed, using Fourier analysis (or another mathematical model), into the sum of fundamental frequency and the harmonic components. They discovered that harmonics are the cause of several problems that affect both the electricity consumers and the supply companies. The affected areas include:

1. Considerable losses in all power distribution cables lead to poor energy efficiency.
2. Larger neutral current than phase currents and tripping of protective systems (breakers and fuses) resulting in outages, all caused by Non-cancellation of triple-N currents.
3. Excess current circulation in distribution transformer windings leads to a reduction in the lifespan, reliability and efficiency of the transformers.
4. Lockup, crash and malfunction of computers.
5. Power factor reduction, etc.

Narinder and Ashwani (2018) review the influence of non-linear load in reactive power compensation using shunt capacitors, which is now becoming difficult as more non-linear loads are coming into the power system circuit. According to Narinder and Ashwani, the distortions in the distribution system currents due to harmonic frequencies are now worrisome when compared to the reactive current of the fundamental frequency. The proliferation of capacitors in the distribution network in recent times due to an increase in electronic device loads has resulted in harmonic amplification, which serves as a sink for harmonic currents and offers a low impedance path for harmonic (or higher) frequencies. George and Agarwal (2007) carried out the capacity analysis in the presence of harmonics using DSP based scheme for distorted current waveform in the presence of non-sinusoidal supply voltage at the Point of Common Coupling (PCC). Singh (2009) evaluated the adverse effects of harmonic distortions and their technical considerations, stressing the influence of harmonic resonance and capacitor overloading.

Eajal and El-Hawary (2010) attempted to resolve the issue of the location and sizing of capacitor banks in power systems where harmonic loads are present by using the Particle Swarm Optimization (PSO) technique for capacitor bank optimal location and sizing. They use the computation of bus voltage Total Harmonic Distortions (THDs) and the minimization of real power as objective functions. In the case of Taher and Bagherpour (2013), hybrid honey bee colony algorithms were dispatched for capacitor bank placement in a power system with the presence of harmonic loads. Research works have clarified that distorted power is more detrimental compared to fundamental reactive power and also not easily quantified, hence, harmonic elimination now becomes a challenging task where multiple harmonic terms are present in supply voltage. Such challenges were addressed by some researchers, two of which works are;

1. Pouresmaeil et al. (2011) use the Shunt Active Power Filter (SAPF) approach to eliminate harmonic by compensating for real and reactive powers. Their methodology was based on Neutral – Point – Clamped (NPC) Voltage Source Inverter (VSI) that easily adapts and actively compensates for harmonic components.
2. Mehrasa et al. (2015) adopted multi-level control of SAPF in the grid system based on Direct Lyapunov (DLP) method to compensate for fundamental and harmonic frequency components of reactive power for harmonic elimination. However, Narinder and Ashwani's (2018) approach to harmonic elimination is a novel approach that can assess various components of capacitors' reactive power due to distorted substation voltage by integrating multi-frequency data structures with the backwards-forward technique of load flow analysis. They adopted the IEEE-1459-2010 standard on the distortion of power terms by considering both the magnitude and phase angle of various harmonic components. The novel approaches decoupled harmonic voltage sources and represent mathematically a substation instantaneous voltage in the presence of harmonics as

$$V_s(t) = \sum_{n=1}^{h_n} \sqrt{2}\, V_{h(s)} Sin(h\omega_0 t + \theta_{V_{h(s)}}) \quad (1)$$

Where h_n is the higher harmonic order in a given power flow analysis $V_{h(s)}$ is the RMS value of h^{th} order substation voltage harmonic relative to reference. The total RMS magnitude of the substation voltage with the presence of harmonics is:

$$[V_{T(S)}]^2 = V_{1(s)}^2 + V_{h(s)}^2 \quad (2)$$

Where $V_{1(s)}$ is the RMS magnitude of fundamental frequency voltage. $V_{h(s)}$ is the total RMS magnitude of harmonic frequency voltage at the substation

$$V_{h(s)}^2 = \sum_{h=2}^{h_n} V_{h(s)}^2 \quad (3)$$

Propagation of the voltage harmonics will flow downstream buses of the distribution system. Hence, the total RMS magnitude of voltage and current phasor in the presence of harmonics at any bus ***i*** downstream are represented as:

$$V_{(i)}^2 = V_{1\,(i)}^2 + V_{h(i)}^2 \quad (4)$$

$$I_{(i)}^2 = I_{1\,(i)}^2 + I_{h\,(i)}^2 \quad (5)$$

Total apparent power as bus ***i*** is

$$S_{(i)}^2 = [V_{(i)}\, I_{(i)}]^2 = [V_{1\,(i)}^2 + V_{h\,(i)}^2]\,[I_{1\,(i)}^2 + I_{h\,(i)}^2] \quad (6)$$

expanding equation 6 gives

$$S_{(i)}^2 = [V_{1\,(i)}\, I_{1\,(i)}]^2 + [V_{1\,(i)}\, I_{h\,(i)}]^2 + [V_{h(i)}\, I_{1(i)}]^2 + [V_{h(i)}\, I_{h(i)}]^2 \quad (7)$$

Separating fundamental from non-fundamental gives

$$S_{(i)}^2 = S_{1(i)}^2 + D_{I(i)}^2 + D_{V(i)}^2 + S_{h(i)}^2 \quad (8)$$

$D_{I(i)}^2$ and $D_{V(i)}^2$ are the current and voltage distortion powers, respectively, while $S_{h(i)}$ is the harmonic apparent power at bus(***i***). The $S_{h(i)}$ can further be split into real and reactive power as follows

$$S_{h(i)}^2 = P_{h(i)}^2 + D_{h(i)}^2 \quad (9)$$

But the harmonic real power, $P_{h(i)}$ is very small

$$\therefore S_{h(i)}^2 \cong D_{h(i)}^2$$

Hence, equation (8) can be represented as

$$S_{(i)}^2 = S_{1(i)}^2 + D_{I(i)}^2 + D_{V(i)}^2 + Q_{h(i)}^2 \quad (10)$$

3. Harmonics Analysis and International Standard Representations

Harmonic is caused by electrical equipment having non-linear current and voltage characteristics or periodically electronically switched loads. The harmonic currents produced by these equipment developed a time-varying flux around the distribution network impedance, which induces a superimposed harmonic voltage upon the supply voltage. The superimposed harmonic voltages have an insignificant effect on the supply voltage due to their relative sum-up value as compared with the supply voltage. Nevertheless, in certain applications, the harmonic voltages can have a large influence and can cause a distorted voltage supply.

According to Singh G. (2009), as far back as 2006, over 70% of the grid loads were estimated to be non-linear loads by 2010. Now that it is over a decade after, definitely, the non-linear loads will have dominated the grid network and can no longer be ignored. In the early nineteenth century, a French mathematician called Jean Baptiste Fourier formulated that a non-sinusoidal periodic function (like non-linear load) having a fundamental frequency (f) can be expressed as the sum of sinusoidal functions of frequencies that are multiple of the fundamental frequency. The formulated mathematical expression has since become one of the major mathematical tools for waveform analysis, referred to as the Fourier series. The general expressions of such a Fourier series for a non-sinusoidal function f(t) are stated below.

$$f(t) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty}[a_n \operatorname{Cos}(2\pi f t) + b_n \operatorname{Sin}(2\pi f t)] \quad (11)$$

Where the DC components are given as

$$a_0 = \frac{2}{T}\int_0^T f(t)\, dt \quad (12)$$

The odd components in the series are given as

$$b_n = \frac{2}{T}\int_0^T f(t) \times Sin(2\pi nft)dt \quad (13)$$

While the even components in the series are

$$a_n = \frac{2}{T}\int_0^T f(t) \times Cos(2\pi nft)dt \quad (14)$$

3.1. Individual and Total Harmonic Distortion

The Individual Harmonic Distortion (IHD) is the ratio of the Root Mean Square (RMS) value of the individual harmonic current or voltage to the RMS value of the fundamental Current or voltage. For harmonic current, it is mathematically expressed as

$$IHD_{h_n} = {I_{(rms)h_n}}/{I_{(rms)h_1}} \quad (15)$$

Where IHD_{h_n} is the individual harmonic distortion of harmonic current with harmonic number h_n.

$I_{(rms)h_n}$ is the rms of harmonic current of harmonic number h_n

$I_{(rms)h_1}$ is the rms of the fundamental current

Likewise, for harmonic voltage, the mathematical expression is

$$IHD_{h_n} = {V_{(rms)h_n}}/{V_{(rms)h_1}} \quad (16)$$

Where IHD_{h_n} is the individual harmonic distortion of harmonic voltage with harmonic number h_n.

$V_{(rms)h_n}$ is the RMS of harmonic voltage of harmonic number h_n

$V_{(rms)h_1}$ is the rms of the fundamental voltage

Equations 15 and 16 are the Institute of Electrical and Electronic Engineers (IEEE) in U.S.A. convention for determining IDH. The European Electro-Technical Commission (IEC) quantifies IHD based on the total RMS value of the waveforms (that is, the summation of both fundamentals and harmonics). For a fundamental RMS current of $I_{(rms)h_1}$ having (n -1) number of harmonics, the total RMS value is expressed as

$$I_{T(rms)} = \sqrt{(I^2)_{(rms)h_1} + (I^2)_{(rms)h_2} + (I^2)_{(rms)h_3} + \cdots + (I^2)_{(rms)h_n}} \quad \ldots \quad (17)$$

Unlike the IHD, the Total Harmonic Distortion (THD) is a term used to represent the deviation of a non-linear waveform from an ideal sinusoidal waveform characteristic.

The THD is defined as the ratio of the RMS value of the harmonics to the RMS value of the fundamental. For a fundamental current of $I_{(rms)h_1}$ the RMS of the harmonics ($I_{H(rms)}$) mathematically expressed as

$$I_{H(rms)} = \sqrt{(I^2)_{(rms)h_2} + (I^2)_{(rms)h_3} + (I^2)_{(rms)h_4} + \cdots + (I^2)_{(rms)h_n}} \quad (19)$$

Hence, the THD is expressed mathematically as

$$THD = {I_{(rms)h_1}}/{I_{H(rms)}} \quad (20)$$

3.2. Effects of Harmonics on the Power Distribution Network

Numerous effects or problems caused by harmonics are being evaluated continuously due to their complex adverse effect on the power system generally. While the influence of harmonic voltages is very loud, harmonic currents are more damaging due to the associated heat loss, which is detrimental to most equipment in the power network. Among these effects are

1. Overheated Transformers
2. Overheated Neutrals
3. Equipment malfunctioning due to excessive voltage distortion
4. Blown Fuses
5. Tripped Circuit Breaker
6. Motor Burn – out etc.

According to Frank Basciano (2023), harmonic currents are the major cause of unwanted side effects in electrical wiring systems. Specifically within power transformers, harmonic currents cause extra heat and mechanical vibration. UL 1561 standards recommended a minimum of 200% transformer full load rating for the neutral bar in K-factor transformers to address the issue of harmonic current. Shamsodin et al. (2012) clarify that the most crucial and major capital investment in distribution and transmission substations is the power transformers.

Their role is critical in power system operations. However, due to the rapid increase of non-linear loads, which increases the harmonics level in the power system, transformer power losses and temperature rise are now a major concern. The effect of harmonic has also caused the Hottest Spot Temperature (HST) of transformers to rise further, resulting in insulation rapid thermal degradation and breakdown.

O'Connell et al. (2012) attribute the deficiency of BS7871 of the IEE wiring regulations, 16th edition, in the UK as a reference to selecting cable sizes for electric circuits on its exclusion of the impact of harmonic distortion in cmmercial and industrial electrical networks. BS7671 only allow for the temperature generated by the fundamental power frequency of a sinusoidal current in a conductor and neglects the associated harmonic components.

The ways to reduce harmonic problems include

1. K - K-rated transformers (using K – factor)
2. Harmonic Mitigating Transformer (HMT)
3. Harmonic filters
4. Delta-Wye Wiring
5. Zigzag Windings

The focus here is the K-factor approach.

3.3. K – Rated Transformer

K-rated transformers, by design, are manufactured to withstand the overheating problems in transformers caused by harmonics. ANSI Standard C57.110-1986 defined a K-factor to determine the magnitude of harmonic current a circuit draws and to determine the heating effect of such harmonic current. Based on a circuit K-factor, transformers are designed and manufactured with a K-rating. It is important to note that K-rated transformers do not reduce harmonics but only indicate the relative ability of a transformer to withstand the harmful effects of harmonics. K-rated transformers increase the size of the core, increase the size of the neutral conductor, and use special winding techniques to reduce eddy current and skin effect losses. K-rated transformers use heavier gauge wires for the primary and secondary coils to reduce the resistance heating. ANSI/IEEE C57. 110-1986 Recommend a capacity de-rating for any transformer carrying non-sinusoidal Load Currents having Total Harmonic Distortion (THD) above 5%. According to Gouda et al. (2011), ANSI/IEEE C57.110 standards consider K-Factor as a means of measuring the thermal effects of non-sinusoidal load on the transformer and an indicator for comparing the heat amount generated by a sinusoidal current with a pure sine wave rms value. The standard or General K-factor rating guidelines are given in Table 3 (Source: Gouda et al. [2011])

3.4. Distribution Transformer Harmonics Measurement

Measurements are critical in engineering system evaluation, assessment and performance analysis. The reliability of the evaluation, assessment and analysis will depend on the accuracy of the measuring instrument. The reliability of measuring instruments, however, is a function of cost. Power system harmonics are measured using Power Quality (PQ) analyzer meters. There are different types of PQ meters; their cost depends on their reliability and extent of data capture capability. A list of measurements that are crucial at the substation distribution transformer outlet, according to Fluke Corporation, is shown in Table 4. The Power quality meter type used for the field measurement exercise is the Lutron DW 6095 power harmonic analyzer.

3.5. Data and Analyses

Harmonics data was collected from two general-purpose distribution substations power transformers on different days at the hours of 9 am, 12 pm and 4 pm for this exercise. The word general purpose in the sense that the load types are not specific because the substation serves areas that incorporate residential, workshops and small offices.

Each substation is located in a different local government in Lagos State. Tables 5, 6 and 7 are the data captured from the two distribution transformers, while tables 9 and 10 are partly data captured at the substitutions. Those were calculated using equations 15 to 20 to determine the harmonics parameters of both the IHD and THD for harmonics distortions associated with the respective substations. Table 8 shows calculated data from the data captured.

Table 3. Standard rating of transformer K-factor for specific load

Load	K-factor
Incandescent lighting (with no solid state dimmers) Electric resistance heating (with no solid state heat controls) Motors (without solid state drives) Control transformers/electromagnetic control devices Motor-generators (without solid state drives)	K-1 K-1 K-1 K-1 K-1
Electric-discharge lighting UPS with optional input filtering Induction heating equipment Welders PLCs and solid state controls (other than variable speed drives)	K-4 K-4 K-4 K-4 K-4
Telecommunications equipment UPS without input filtering Multi-wire receptacle circuits in general care areas of health care, facilities and classrooms of schools, etc. Multi-wire receptacle circuits supplying inspection or testing equipment on an assembly or production line,	K-13 K-13 K-13 K-13
Mainframe computer loads Solid state motor drives (with heat controls) Multi-wire receptacle circuits in critical care areas and operating/recovery rooms of hospitals	K-20 K-20 K-20
Multi-wire receptacle circuits in industrial, medical, and educational laboratories Multi-wire receptacle circuits in commercial office spaces Small mainframes (mini and macro)	K-30 K-30 K-30
Other loads identified as producing very high amounts of harmonics (especially in higher orders)	K-40

Table 4. Measurements at the outlet point of the distribution transformer

S/N	Measurement	Look for
1.	kVA	Transformer loading. If loading exceeds 50%, check for harmonics and possible need for de-rating.
2.	Harmonic spectrum	a. Harmonic orders/amplitudes present: 3rd harmonic (single-phase loads) 5th, 7th (primarily three-phase loads) b. Resonance of higher order harmonics c. Effectiveness of harmonic trap filters
3.	THD	Harmonic loading within limits: Voltage % THD < 5% Current % THD < 5 – 20 %
4.	K - factor	Heating effect on transformer from harmonic loads
5.	Ground currents	a. Objectionable ground currents are not quantified but are prohibited by NEC b. Neutral – ground bond in place c. ESG (Electrical Safety Ground) connector to the ground electrode (typically building steel) in place

Source: Fluke Digital Library@www.fluke.com/library (2023)

Table 5. Distribution substation 'A' Data rating: 500kVA (General purpose)

Time	V_{1N} (V)	V_{2N} (V)	V_{3N} (V)	I_1 (A)	I_2 (A)	I_3 (A)	S_1 (kVA)	S_2 (kVA)	S_3 (kVA)	S_T (kVA)
9 a.m.	223.7	224.2	218.4	501.6	521.3	488.3	112.2	116.9	106.6	335.7
12 p.m.	219.4	220.5	215.2	521.3	493.6	501.5	114.4	108.8	107.9	331.1
4 p.m.	220.1	218.8	221.1	487.5	503.4	479.1	107.3	110.1	105.9	323.3

Table 6. Distribution substation 'B' Data Rating: 500kVA (General purpose)

Time	V_{1N} (V)	V_{2N} (V)	V_{3N} (V)	I_1 (A)	I_2 (A)	I_3 (A)	S_1 (kVA)	S_2 (kVA)	S_3 (kVA)	S_T (kVA)
9 a.m.	231.2	227.4	230.2	498.8	463.2	423.4	115.3	105.3	97.5	318.1
12 p.m.	228.0	225.9	230.1	438.2	482.9	453.6	99.9	109.1	104.4	313.4
4 p.m.	230.0	229.2	228.4	463.7	451.0	442.2	106.7	103.4	101	311.1

Table 7. Distribution substations A and B harmonic currents data

Harmonic No. (h)	Distribution Transformer 'A'			Distribution Transformer 'B'		
	I_{Red} (A) 9 a.m	I_{Yellow} (A) 12 p.m	I_{Blue} (A) 4 p.m	I_{Red} (A) 9 a.m	I_{Yellow} (A) 12 p.m	I_{Blue} (A) 4 p.m
1	501.6	521.3	488.3	492.8	463.4	423.4
3	98.2	158.3	46.7	192.4	201.2	185.2
5	52.4	87.8	195.5	125.1	118.0	142.1
7	10.0	56.4	78.3	85.3	78.0	92.3
9	0.00	25.0	48.2	52.5	52.5	37.5
11	6.00	0.00	23.1	18.6	20.1	8.2
13	4.00	14.3	0.00	5.30	12.4	14.6
15	0.00	12.2	13.5	0.00	8.30	0.00
17	2.40	0.00	5.00	2.00	0.00	4.20
19	0.00	6.00	1.00	3.20	3.40	2.00
21	0.00	0.00	2.00	1.00	1.50	1.00

Table 8. Calculated total harmonics and true RMS values per phase

Distribution Transformer	Total Harmonics RMS, I_{TH} (A)			Total RMS Current, I_T (A)		
	I_R (A)	I_Y (A)	I_B (A)	I_R (A)	I_Y (A)	I_B (A)
A	112	192.2	222.7	514	555.6	536.7
B	251.1	252.8	254.5	553.1	527.7	494

Table 9. Distribution substation 'A' Data, IHD and THD analysis (9 a.m)

Harmonic No. (h)	RED PHASE			YELLOW PHASE			BLUE PHASE		
	I (A)	IHD (IEEE) (%)	IHD (IEC) (%)	I (A)	IHD (IEEE) (%)	IHD (IEC) (%)	I (A)	IHD (IEEE) (%)	IHD (IEC) (%)
1	501.6	100	97.6	521.3	100	93.8	488.3	100	91.0
3	98.2	19.6	19.1	158.3	30.4	28.5	46.7	9.56	8.70
5	52.4	10.4	10.2	87.8	16.8	15.8	195.6	40.1	36.4
7	10.0	1.99	1.9	56.4	10.8	10.2	78.3	16.0	14.59
9	0.00	0.00	0.00	25.0	4.80	4.50	48.2	9.87	9.00
11	6.00	1.20	1.16	0.00	0.00	0.00	23.1	4.73	4.30
13	4.00	0.80	0.78	14.3	2.74	2.57	0.00	0.00	0.00
15	0.00	0.00	0.00	12.2	2.34	2.20	13.5	2.76	2.52
17	2.40	0.48	0.47	0.00	0.00	0.00	5.00	1.02	0.93
19	0.00	0.00	0.00	6.00	1.15	1.08	1.00	0.20	0.19
21	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.41	0.37
THD		22.3	21.8		36.9	34.6		45.6	41.5

Table 10. Distribution substation 'B' Data, IHD and THD analysis (9 a.m)

Harmonic No. (h)	RED PHASE			YELLOW PHASE			BLUE PHASE		
	I (A)	IHD (IEEE)	IHD (IEC)	I (A)	IHD (IEEE)	IHD (IEC)	I (A)	IHD (IEEE)	IHD (IEC)
1	492.8	100	89.1	463.2	100	87.9	423.4	100	85.7
3	192.4	39.0	34.8	201.2	43.4	38.2	185.2	43.7	37.5
5	125.1	25.4	22.6	118.0	25.5	22.8	142.1	33.6	28.8
7	85.3	17.3	15.4	78.0	16.8	14.8	92.3	21.8	18.7
9	52.5	10.7	9.49	52.5	11.3	9.96	37.5	8.86	7.59
11	18.6	3.77	3.36	20.1	4.34	3.81	8.2	1.94	1.66
13	5.30	1.10	0.96	12.4	2.68	2.35	14.6	3.45	2.96
15	0.00	0.00	0.00	8.30	1.79	1.57	0.00	0.00	0.00
17	2.00	0.41	0.36	0.00	0.00	0.00	4.2	9.92	0.85
19	3.20	0.65	0.58	3.40	0.73	0.64	2.0	0.47	0.40
21	1.00	0.20	0.18	1.50	0.32	0.28	1.5	0.38	0.30
THD		51.0	45.4		58.0	47.9		60.1	51.5

3.5. Distribution Transformer K – Factor Computation

The K value is an indicator for determining the ability of the transformer to withstand harmonic currents without outshooting its rated maximum temperature when supplying loads characterized by harmonic content. K-factor values range from 1, representing linear loads, to 50, representing the worst harmonic-infested load. According to Frank Basciano (2023), K-factor of 4 and 13 ratings are common and frequently specified and installed. Transformers are sometimes manufactured to rated K-factor value and are said to be K-rated transformers with the K value stated on the transformer nameplate. Just as in the case of harmonics distortion computations, the IEEE or IEC approach can be used to determine the K – factor of a transformer as long as the method used is clearly specified.

3.5.1. IEEE Method OF K – Value Computation

The mathematical expression for K- factor is

$$K = \sum_{h=1}^{h} (I_{h(pu)})^2 h^2 \quad (21)$$

Where

$$I_{h(pu)} = I_{h\neq 1} / I_1 \quad (22)$$

$I_{h\neq 1}$ *is the harmonics components*
I_1 *is the fundamental current*

Using 9a.m data collation for substation 'A', Equations (21) and (22) are used, with the relevant ones from equations (1) to (11), to compute the K – factor by IEEE method for substations Power transformer in tables 11 and 12

3.5.2. IEC Method of k – Value Computation

The mathematical expression for K – factor computation using the IEC method is the same equation (21) used for the IEEE method.

The only variation is the denominator of the $I_{h(pu)}$, which is no longer the fundamental frequency current but the total RMS current, just as in the case of the THD IEC computation method. Hence, the mathematical expression for $I_{h(pu)}$ value using IEC is

$$I_{h(pu)} = I_{h\neq 1} / I_{T(rms)} \quad (23)$$

$I_{T(rms)}$ expression is still the same equation (17)

Table 11. Substation 'A' K – factor evaluation (IEEE method)

Harmonic No. (h)	RED PHASE			YELLOW PHASE			BLUE PHASE		
	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$
1	501.6	1.000	1.000	521.3	1.000	1.000	488.3	1.000	1.000
3	98.2	0.196	0.346	158.3	0.304	0.832	46.7	0.096	0.083
5	52.4	0.104	0.270	87.8	0.168	0.706	195.6	0.401	4.020
7	10.0	0.020	0.019	56.4	0.108	0.572	78.3	0.160	1.254
9	0.00	0.000	0.000	25.0	0.048	0.187	48.2	0.099	0.794
11	6.00	0.012	0.017	0.00	0.000	0.000	23.1	0.047	0.267
13	4.00	0.008	0.011	14.3	0.027	0.123	0.00	0.000	0.000
15	0.00	0.000	0.000	12.2	0.023	0.119	13.5	0.028	0.176
17	2.40	0.005	0.007	0.00	0.00	0.000	5.00	0.010	0.029
19	0.00	0.000	0.000	6.00	0.012	0.052	1.00	0.002	0.001
21	0.00	0.000	0.000	0.00	0.000	0.000	2.00	0.004	0.007
K-Factor			1.670			3.591			7.631

Table 12. Substation 'B' K – factor evaluation (IEEE Method)

Harmonic No. (h)	RED PHASE			YELLOW PHASE			BLUE PHASE		
	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$
1	492.8	1.000	1.000	463.2	1.000	1.000	423.4	1.000	1.000
3	192.4	0.390	1.369	201.2	0.408	1.498	185.2	0.437	1.719
5	125.1	0.254	1.613	118.0	0.239	1.428	142.1	0.336	2.822
7	85.3	0.173	1.467	78.0	0.158	1.223	92.3	0.218	2.329
9	52.5	0.107	0.927	52.5	0.107	0.927	37.5	0.089	0.642
11	18.6	0.038	0.175	20.1	0.041	0.203	8.20	0.019	0.044
13	5.30	0.011	0.020	12.4	0.025	0.106	14.6	0.034	0.195
15	0.00	0.000	0.000	8.30	0.017	0.065	0.00	0.000	0.000
17	2.00	0.004	0.005	0.00	0.000	0.000	4.20	0.010	0.029
19	3.20	0.006	0.013	3.40	0.007	0.018	2.00	0.005	0.009
21	1.00	0.002	0.002	1.50	0.003	0.004	1.50	0.004	0.007
K-Factor			6.591			6.472			8.796

Table 13. Substation 'A' K – factor evaluation (IEC method)

Harmonic No. (h)	RED PHASE			YELLOW PHASE			BLUE PHASE		
	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$
1	501.6	0.976	0.953	521.3	0.938	0.879	488.3	0.910	0.828
3	98.2	0.191	0.328	158.3	0.285	0.731	46.7	0.087	0.068
5	52.4	0.102	0.260	87.8	0.158	0.624	195.6	0.364	3.312
7	10.0	0.019	0.018	56.4	0.102	0.510	78.3	0.146	1.044
9	0.00	0.000	0.000	25.0	0.045	0.164	48.2	0.090	0.656
11	6.00	0.012	0.017	0.00	0.000	0.000	23.1	0.043	0.224
13	4.00	0.008	0.011	14.3	0.026	0.114	0.00	0.000	0.000
15	0.00	0.000	0.000	12.2	0.022	0.109	13.5	0.025	0.141
17	2.40	0.005	0.007	0.00	0.00	0.000	5.00	0.009	0.023
19	0.00	0.000	0.000	6.00	0.011	0.044	1.00	0.002	0.001
21	0.00	0.000	0.000	0.00	0.000	0.000	2.00	0.004	0.007
K-Factor			1.594			3.175			6.304

Table 14. Substation 'B' K – factor evaluation (IEC method)

Harmonic No. (h)	RED PHASE			YELLOW PHASE			BLUE PHASE		
	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$	I (A)	I_{pu}	$(I_{pu})^2h^2$
1	492.8	0.891	0.794	463.2	0.878	0.771	423.4	0.857	0.734

3	192.4	0.348	1.090	201.2	0.381	1.306	185.2	0.375	1.266
5	125.1	0.226	1.277	118.0	0.224	1.254	142.1	0.288	2.074
7	85.3	0.154	1.162	78.0	0.148	1.073	92.3	0.187	1.713
9	52.5	0.095	0.731	52.5	0.099	0.794	37.5	0.076	0.468
11	18.6	0.034	0.140	20.1	0.038	0.175	8.20	0.017	0.035
13	5.30	0.010	0.017	12.4	0.023	0.089	14.6	0.030	0.152
15	0.00	0.000	0.000	8.30	0.016	0.058	0.00	0.000	0.000
17	2.00	0.004	0.005	0.00	0.000	0.000	4.20	0.009	0.023
19	3.20	0.006	0.013	3.40	0.006	0.013	2.00	0.004	0.006
21	1.00	0.002	0.002	1.50	0.003	0.004	1.50	0.003	0.004
K-Factor			5.231			5.537			6.475

Using 9a.m data collation for substation 'A', equations (21) and (23) are used, with the relevant ones from equations 1 to 11, to compute the K – factor by IEC method for substations Power transformer in Tables 13 and 14. The K-factor values are derived from data found in the recommended procedure for developing power distribution transformer capability in both the liquid-immersed and dry-type when supplying non-sinusoidal load currents, as stated in ANSI/IEEE C57.110-2018. The K-factor is a transformer de-rating factor that identifies a transformer's specific non-linear load capability or the amount of oversizing required to accommodate the load. IEEE C57.96 and IEEE C57.110 are standards that apply to transformers with a K-factor rating. Since the UL and CSA standards also reference these IEEE standards, they are equally relevant and legitimate. Both general-purpose and K-factor rated transformers must adhere to all of these strict requirements.

4. Result Analysis

The K-Factor results derived from the field data are shown in Tables 13 and 14. Virtually all our distribution transformers in the distribution network are injected without factoring in the possibility of non-linear loads in the distribution system. Though large numbers of the distribution transformers are very old, and among them are those that have spent their lifespan based on their operation capacity and years in operation. While Nigeria's generating capacity is grossly inadequate in meeting electricity market demand and equipment in the network is insufficient and old, losing such equipment due to negligence of power quality consideration and evaluation will further cause more setbacksss to our electricity utility system. For this reason, data acquisition and analysis which produce results such as the one in Tables 13 and 14 cannot be dispensed with are inevitable. Table 13 shows the existence of a harmonics load connected to the transformer or evidence of a non-linear load of considerable size in the distribution network. Table 14, however, is able to show the K-value of the transformers in operation, which are tools for transformers supplying non-linear load de-rating in order to protect the transformer from breakdown due to thermal heat produced by harmonics.

4.1. Result Interpretation

Results need to be analyzed to know the status of the system under consideration, to establish operation parameters, to draw behavior comparisons with respect to standard regulations and practice etc. Considering Table 15 not only does it reflect the presence of non-linear load in the network, the values are higher than the 20% maximum recommended for safe and healthy operations of the transformers (See Table 3 for recommended value). The THD values of Transformer B are worse, and urgent de-rating using the K value is important to keep the transformer in operation. Also, variation in harmonics values in phases could reflect imbalance loading of the transformers. Using Table 17, we can select a suitable operation K value for substations A and B, especially when the K factor transformer is to be selected for a new distribution substation. For the selection of transformer for the substations, considering the results in Table 16, a K-factor of 13 ratings will be selected for substation A since the K value is higher than 4 but less than 13, while a K-factor of 20 suffices for substation B. Also, from Table 17, the non-linear loads in percentage aggregate can be determined for the K-values obtained for the substations in Table 16. As shown in Table 17, 35-75% of loads in substation A are non-linear loads and generate harmonics, while 60-100% of loads in substation B are non-linear loads and generate harmonics. Lastly, the K values are reliable values for transformer de-rating.

Table 15. Distribution power transformer Total Harmonics Distortion (THD)

Distribution Substation Power Transformer	**Total Harmonics Distortion (THD) Per Phase (%)**						**THD Average (%)** $THD_{3-\theta} = (\sum_{i=1}^{3} THD_i)/3$	
	Red Phase		Blue Phase		Yellow Phase		IEEE Method	IEC Method
	IEEE	IEC	IEEE	IEC	IEEE	IEC		
A	22.3	21.8	36.9	34.6	45.6	41.5	34.9	32.6
B	51	45.4	58.0	47.9	60.1	51.5	56.4	48.3

Table 16. Distribution power transformer K – factor values

Distribution Substation Power Transformer	K - Factor Per Phase						K-Factor (3-phase) $K_{3-\theta} = (\sum_{i=1}^{3} K_i)$	
	Red Phase		Blue Phase		Yellow Phase		IEEE Method	IEC Method
	IEEE	IEC	IEEE	IEC	IEEE	IEC		
A	1.670	1.594	3.591	3.175	7.631	6.304	12.89	11.073
B	6.591	5.231	6.472	5.537	8.630	6.474	21.69	17.24

Table 17. General K factor rating guidelines

K-factor	Description	Harmonics activity guide	Pricing
K1	Standard transformer, general purpose, standard lighting, motors without drives	Little to no harmonics generating loads, typically<15%	Standard prices
K4	Induction heating, SCR drives, AC drives	Up to 35%of loads generate harmonics	Standard prices+$
K13	Institutional electronically controlled lighting, school, hospital, etc.	35-75% of loads generate harmonics	Standard prices+$$
K20	Equipment includes a Data processor, computer server, essential hospital care facilities and operating rooms	60-100% of loads generate harmonics	Standard prices +$$$
K30-50	Loads known generate harmonics with extra k-factor strength.	100% of loads generate harmonics .known harmonics signature	Standard prices +$$$$

Source: ABB Technical Paper 2023

5. Conclusion and Recommendations

5.1. Conclusion

Generally, substations are installed in Nigeria without prior evaluation of the load characteristics to support the selection of the distribution transformer suffices for the locality. Considering the technological trends and non-linearity loads proliferation in our distribution network, load assessment of our distribution substation transformers is essential to increase their life span.

The magnitude of the Total Harmonic Distortion (THD) computed shows values that are twice the maximum value of 20% recommended. Hence, there is a need to reduce the harmonics impact to avoid overheating and burning of the substation transformer. Also, such exercise should be carried out in most of our distribution substations in other to take measures that will increase their life span and reduce the cost of maintenance.

5.2 Recommendations

The extent of harmonics caused by the non-linear load in the distribution network required that urgent steps be taken to minimize the effect. Either of the following steps is suitable;

1. Using the k-factor to de-rate the transformer is highly recommended for the current situation since it is still the cheapest means
2. Replacing the existing transformer with the k-rated or harmonics compliance transformer is another option but will require more financial commitment.
3. Adding more transformers to the distribution substations to relieve the existing transformers of excess harmonics.

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