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Modelling and Evaluation of Load-Side Generated Harmonics in Electrical Systems of Sub-Saharan Africa: Challenges and Solutions

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***Abstract*— The evaluation, analysis, and mitigation of harmonics in electrical power systems has become one of the significant topics in power systems today and one that many researchers are focusing on intently. This paper defines harmonics and its sources in the power system, discusses its impact on the power system equipment and its effects on the economic side of power system management, and discusses mitigation techniques being discussed by researchers worldwide and in Sub-Sahara Africa.**

This paper aims to highlight the challenges faced in the Sub-Sahara African regions in relation to harmonics, including the possible solutions and government policies that can be adopted to address power quality concerns in the region better.

Keywords—harmonics; power system; smart meters; power analysers; harmonic filters

I. INTRODUCTION TO HARMONICS IN ELECTRICAL SYSTEMS

In electrical systems, harmonics can be defined as the voltage and current sinusoidal waveform distortion. Alternating currents, known for their sinusoidal waveforms, are distorted due to harmonics in the system. The harmonics occur at multiples of the fundamental frequency, with the more common and problematic ones being the odd-order harmonics [1]. Most research on harmonics focuses on the lower odd-order harmonics since the harmonics' magnitude decreases with the harmonics' order. Figure 1.1 shows the effect of the harmonics on the original waveform.

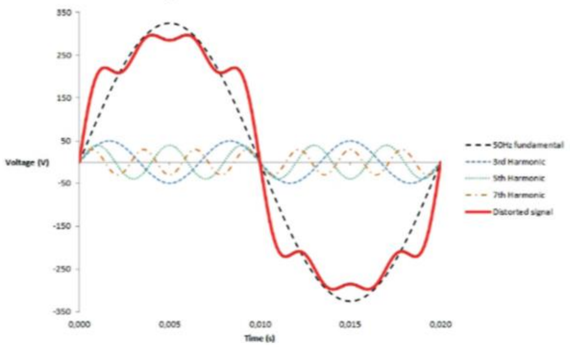

Figure 1.1: A Distorted Waveform [1].

II. SOURCES AND IMPACT OF HARMONICS

A. Sources of Harmonics

According to [2] the sources of these harmonics in electrical power systems are referred to as non-linear loads. Common non-linear loads in power systems include the following [3].

1) Variable Frequency Drives (VFDs)

By altering the frequency and voltage of the electricity provided to electric motors, variable frequency drives, VFDs, are frequently employed in industrial settings to regulate the torque and speed of these machines. While VFDs offer significant energy savings and operational flexibility, they are also a notable source of harmonics in power systems. VFDs operate by converting fixed-frequency AC power into variable-frequency AC power. This is achieved through three main components: a rectifier, a DC bus, and an inverter. The input AC voltage is first converted to DC voltage using a rectifier. This stage often employs diodes or thyristors and introduces a non-linear current draw from the AC supply, a primary harmonics source. The DC voltage is stored in capacitors within the DC bus.

The energy can be buffered, allowing for smoother operation and reduced voltage fluctuations. The DC voltage is then converted back to AC using an inverter, which controls the output frequency and voltage supplied to the motor. This process also introduces switching frequencies, which can create additional harmonics. During the rectification phase, VFDs draw current in a non-linear fashion. Instead of drawing current uniformly throughout the AC cycle, the rectifier draws current in short pulses, particularly at the peak of the voltage waveform. This results in a distorted current waveform, creating harmonics in the power system. The harmonic currents generated by the rectifier are primarily odd harmonics (3rd, 5th, 7th, etc.), which can significantly affect power quality. The magnitude and order of these harmonics depend on the configuration of the rectifier and the load conditions. The inverter portion of a VFD switches on and off rapidly to create the desired output frequency. This switching can introduce high-frequency harmonics into the system, further complicating the harmonic profile. Most VFDs utilize Pulse Width Modulation (PWM) techniques to control the voltage and frequency output. The PWM process generates harmonics at multiples of the switching frequency, which can be problematic, especially in sensitive applications.

2) Switched Mode Power Supplies (SMPS)

Typically found in computers, Televisions, chargers, and many electronic devices. The switching action within these supplies generates harmonics, particularly higher-order harmonics. Most of today's electronic devices are embedded with Switched Mode Power Supplies, and the name is based on the switching and conversion of unregulated DC input voltage to a regulated DC output voltage. Based on the SMPS principle of operation, where rectifying and filtering at various stages are involved, the result is in the demand of pulses of current instead of continuous current. This pulse is made of high content of harmonics of the third order and even higher orders [1].

3) Uninterruptible Power Supplies (UPS)

Uninterruptible Power Supplies (UPS) are crucial for maintaining a steady power supply to sensitive electronic equipment. However, they can also be a source of harmonics, leading to various power quality issues.UPS systems often serve non-linear loads, such as computers and servers, which inherently generate harmonics due to their switching power supplies.: Different types of UPS, such as line-interactive and double-conversion, can produce varying levels of harmonics. For example, double-conversion UPS systems can generate harmonics during the inverter operation. The rectifier in a UPS converts AC to DC and can be a significant source of harmonics, particularly in systems using diode-based rectifiers. They can create current harmonics that can propagate back into the electrical network.

4) Compact Fluorescent Lamps (CFLs) and LED Lights with Electronic Ballast

Traditional fluorescent lights with magnetic ballasts have minimal harmonic distortion. However, modern fluorescent and LED lights often use electronic ballasts that can introduce harmonics, particularly the 3rd and 5th harmonics. Compact Fluorescent Lamps (CFLs) and light-emitting diodes (LEDs) with electronic ballasts are widely used lighting technologies known for their energy efficiency and long lifespan. However, both technologies can be significant sources of harmonics in electrical systems. CFLs pass an electric current through a gas-filled tube, which excites the gas and produces ultraviolet light. This light then interacts with a phosphor coating on the inside of the lamp, producing visible light. CFLs require a ballast to regulate the current flowing through the lamp. Electronic ballasts are commonly used because they improve efficiency and reduce flicker.

LEDs generate light through electroluminescence, where electrons recombine with holes within the semiconductor material, releasing energy in the form of light. LED lights require electronic drivers to convert AC voltage to the appropriate DC voltage and to manage the current supplied to the LEDs. CFLs and LED lights with electronic ballasts and drivers are considered non-linear loads. This means that they draw current in a way that is not directly proportional to the voltage, leading to the generation of harmonics. The electronic ballasts and drivers rapidly switch on and off to regulate the current, creating sharp current waveforms. This switching action leads to distortion in the current waveform, producing harmonics. The electronic ballasts and LED drivers use switching power supply techniques to manage power efficiently. These switching operations can introduce high-frequency harmonics into the electrical system, especially at multiples of the switching frequency. Furthermore, many LED drivers utilize PWM to control brightness levels. This technique rapidly changes the current flow, further contributing to harmonic distortion.

5) Rectifier Circuits

A rectifier circuit is an electrical component that converts alternating current (AC) to direct current (DC). Commonly used in power supplies for various applications, rectifiers can be classified into half-wave and full-wave configurations. While they serve essential roles in power conversion, rectifier circuits are significant sources of non-linear loads due to their operational characteristics. Rectifiers typically utilize diodes, which have a non-linear voltage-current relationship. This behavior results in non-linear current waveforms, especially when the diodes switch on and off during the AC cycle. The abrupt changes in current during the rectification process introduce harmonics into the electrical system. These harmonics distort the fundamental frequency, affecting overall power quality. Rectified output is not a pure DC but contains ripple voltage, which can lead to fluctuating load conditions, further contributing to non-linear load characteristics.

6) Arc Furnaces

High power consumption devices, such as arc furnaces and welders, cause correspondingly high levels of harmonic distortion in a power network. Applications for arc furnaces include melting, refining, and air refining. These stages result in gradients of various levels and harmonics.

Furnaces create significant harmonic distortion due to the arcing process between electrodes and the charge material used for metal melting. The random variation of the arc produces a combination of ignition delays and voltage changes. This situation creates some harmonic spectrum with odd and even multiples of fundamental frequency. These frequencies change intermittently with various swift rise and fall levels [1].

7) Welding Equipment

Welding equipment, such as arc welders, MIG, and TIG machines, is categorized as a non-linear load due to its operational characteristics. Non-linear loads are those where the current does not vary directly to the voltage, leading to various electrical challenges. Many modern welding machines use inverters to convert DC to AC and control the welding process. While efficient, inverters can produce harmonics that distort the current waveform. The dynamic nature of the welding arc creates variations in current and voltage. When the arc is initiated or adjusted, it causes rapid changes in load, contributing to non-linear behavior. Techniques like pulsed MIG welding involve rapid on/off cycling of the current, which generates non-linear loads as the power demand fluctuates significantly during operation. If welding equipment incorporates motors (e.g., wire feeders), these can also introduce non-linear characteristics due to their operational behavior, especially during start-up and load changes.

8) Magnetizing Currents of Transformers

Unless the transformer is in a core saturation condition, a transformer operating normally does not produce any harmonic distortion. Magnetizing currents in transformers can generate harmonics through non-linear characteristics and saturation effects in the transformer core. Transformers operate on the principle of electromagnetic induction, where an alternating current (AC) in the primary winding induces a magnetic field in the core, which then causes a current in the secondary winding. The magnetizing current is required to establish a magnetic field in the transformer. The magnetizing current is not constant; it varies with the applied voltage and the magnetic properties of the transformer core material. When the transformer is energized, the magnetizing current includes a reactive component (due to inductance) and a resistive component (due to core losses). Most transformers use silicon steel or other ferromagnetic materials for the core. These materials exhibit a non-linear magnetization curve, meaning their permeability (the ability to conduct magnetic lines of force) changes with the magnetic field strength. As the magnetic field increases, the core eventually reaches saturation. When the magnetic core becomes saturated, it can no longer effectively support an increased magnetic flux. As a result, the inductance of the transformer decreases significantly, and the current drawn by the transformer does not remain sinusoidal. As the core saturates, the magnetizing current waveform distorts, typically resulting in a sharp rise in current during the peaks of the AC cycle. This non-linear response causes the current to include harmonics, as the current waveform no longer follows the sinusoidal shape of the voltage waveform. In addition, when a transformer is energized, it experiences an inrush current that can be many times greater than the standard magnetizing current. This inrush current also includes significant harmonic content due to the rapid change in current as the transformer approaches saturation.

9) Rotating Machines

Generators and Motors are examples of rotating machines that produce magnetizing fields like transformers. Hence, they are capable of producing harmonics in power networks. Though the harmonic content produced due to the magnetization curve of motors is much more linear when compared to that produced by a transformer, the harmonic content is not disturbing; however, the higher-capacity motors can generate high harmonic content. On the other hand, generators produce observable voltage harmonics following the unpractical nature of the spatial distribution of the stator winding. The voltage harmonics a generator produces are the 3rd-order harmonics, which, in turn, create a 3rd-order current harmonic in the power network [1].

B. Impact of Harmonics on Electrical Systems and Equipment

While discussing harmonics and its sources in electrical power systems, examining its impact or effect on the system and equipment connected is important.

1) Impact on Utility and End-Users

[4] categorized the effects of harmonics in two; its impact on utility and the end-user. The implications for utility discussed includes resonance, tripping of sensitive loads, problems with capacitors in the system, and overheating of transformers.

- Resonance: can occur when non-linear loads inject harmonic currents. These harmonic currents can produce high harmonic voltages that cause noises in some electrical components and equipment and can cause damage to the equipment.
- Tripping of Sensitive Loads: like equipment or machines used in hospitals or other critical infrastructure. [4] found that significant tripping in the electrical power system can occur at 10% voltage distortion.
- Problems with Capacitors in the System, the common issues can include failing of the capacitor cells, degrading of its internal capacitance, and damage to the capacitor fuse.
- Overheating of transformers: when not fully loaded, the transformers can overheat due to harmonic distortion in the electrical system. Even when fully loaded, the transformers are heated beyond a level that its power rating can explain. Two reasons for this overheating are increased losses due to harmonic current and the effect of the transformers' resistive skin.

The impact on the end-user includes malfunctioning digital clocks, interference with telephone lines, heating of motors in domestic electrical appliances, and overloading of the neutral conductors.

2) Impact on the Electrical Power System

[5] summarized the impacts of harmonics on the electrical power system as the following:

- It can cause interference with telephone lines and other communication signals.
- It can lead to errors in sensitive or precision equipment. Their operation and control can be affected.
- It can lead to overcurrent in the neutral of equipment and distribution networks.
- It can cause the circuit breakers and relays in the network to trip.
- It can lead to equipment failure in the network, including the power transformers.
- It can lead to overheating of the transformers in the network.

C. *Overview of Power Quality Issues in Sub-Saharan Africa*

A significant amount of research has been done on harmonics in Africa, particularly in Sub-Saharan Africa. Since the 2010s, researchers in Nigeria, Ghana, and Uganda have researched harmonic measurement under various conditions and studied its impact, the sources of harmonics, and methods for mitigating harmonic distortion in electrical power systems.

[6] studied the impact of harmonic distortion on the different voltage levels in a network. Using version 19 of the Electrical Transient Analyzer Program (ETAP), the work simulated a network of 132 kV, 33 kV, and 11 kV voltage levels. The research showed that harmonic content is more prevalent in the lower voltage level networks than in higher voltage levels. The harmonic content found in the network was also compared to the IEC standard, and they discovered that some parts of the network violated the standards provided.

Likewise, the effects of energy-efficient lamps, light-emitting diode (LED) lamps, and compact fluorescent lamps (CFLs) have been studied in Ghana. In previous research, energy-saving lamps are sources of harmonic content in electrical power systems and contribute to significant harmonic content toomes [7]. Field measurements were carried out at the point of common coupling (PCC) to determine the effects of these energy-efficient lamps on the electrical power system, and the results of the measurement were verified using a simulation of the network. The measurements showed that the LED lamps generate more harmonic content than the CFLs, and the maximum loading for both lamps was identified during the research. [8].

[9] studied harmonics in the 330 kV network from generation stations to transmission stations in Nigeria. A total of 52 buses were simulated and an analysis of the harmonic content in the network was carried out research carried out by [10] showed that all the buses in Afe Babalola University (ABUAD), Nigeria, measured harmonic distortion beyond the limit provided by the International Electrotechnical Commission (IEC) 61000, Institute of Electrical and Electronics Engineers (IEEE) 519, and European Standard (EN) 50160 standards. [11] in Addis Ababa, studied the effect of harmonics in the degrading process of the light rail transit commissioned in 2015. Using mathematical analysis and modelling of the transit components, the study found that the harmonic distortion in the system exceeded the IEEE 519-1992 standard. MATLAB simulations showed that implementing appropriate filters would significantly reduce the harmonics of the system below the standard limit.

III. Harmonic Modelling Techniques

Modeling techniques are essential to analyze and further mitigate the harmonic content in a power system. These techniques help to provide more explicit detail about the harmonic content in the system so that harmonic content can be better understood, its sources in the system and the level of harmonic content. They can also be used for predictive analysis of the harmonic distortion in the system.

A. *Models Used for Simulating Load Side Harmonics*

Some of the models used for the analysis of harmonics are discussed.

1) *Fast Fourier Transform*

Fourier analysis is generally applied when converting periodic waveforms in the time domain to their corresponding representation in the frequency domain or when converting waveforms in the frequency domain to the time domain. Alternating current as a sinusoidal signal is periodic; therefore, the fourier analysis can be used in its evaluation. Fourier analysis of a distorted signal shows the amplitude and phase of the fundamental and harmonic signals [12]. Fast Fourier transform (FFT) is a more efficient implementation of the discrete fourier transform (DFT). Usually, FFT requires only one measurement or "snap-shot," according to [13]. [13] discussed the conditions for using FFT to achieve accurate analytical results.

- The sampled periods must be integers. Otherwise, multiple snap-shots will be required.
- The signal to be analyzed must be static.
- Interharmonics must not be present in the signal. This means all the frequencies must be integer multiples of the fundamental frequency.
- If f_s is the sampling frequency and f_w is the signal's highest frequency, then $f_s > 2 \times f_w$

An improvement on the FFT, called the short-time fourier transform (STFT), is derived by a process called windowing, which involves analyzing a "short time" in the signal. [12] defines the STFT as the "sliding window version of FFT" since it only considers a very small signal size as it moves through the signal.

2) *Wavelet Transform (WT)*

Wavelet analysis of the distorted signal generates approximations of the distorted signal, categorizing them into high and low frequencies appropriately [14]. This means it can be applied to a broader range of frequencies and not restricted to any frequency domain. A waveform or signal's frequency and time details can be extracted using wavelet transform [15]. Analysis derived from the wavelet transform of distorted signals can be used to track the time evolution of the signal components. The harmonic components and the subharmonic and interharmonic components can also be tracked. Other models derived from the wavelet analysis include the digital wavelet transform (DWT), continuous wavelet transform (CWT), and wavelet packet transform (WPT) [16].

3) *Harmonic Power Flow Analysis*

This method involves deriving the power system impedance matrix through its admittance matrix. This means an inverse operation must be done on the admittance matrix, and the admittance matrix can be calculated using equation 2.1.

$$V_{bus}^{h} = (Y_{bus}^{h})^{-1} . I_{bus}^{h} \quad (1)$$

where

V_{bus}^{h} is the voltage matrix at the h-order harmonics
Y_{bus}^{h} is the admittance matrix at the h-order harmonics
I_{bus}^{h} is the current matrix at the h-order harmonics

Methods like the Newton-Raphson and Gaussian methods are typically used to solve for the harmonic power flow analysis. These methods can be tedious and time-consuming, so some software tools are used. [17] used the open distribution system simulator (OpenDSS to compute the harmonic power flow and fundamental power flow analysis to provide harmonic analysis of a distribution network. On the other hand, [18] modified the Matpower simulation package to solve for the network's harmonic power flow analysis. However, this model has several limitations since it is prone to errors due to harmonic resonance in the power system.

B. *Comparison of Different Harmonic Estimation Methods*

Comparing the fourier transform models to the wavelet transform models leads to the conclusion that either one can be applied to cover for the limitations of the other. While the fourier transform models are more straightforward to implement with a relatively low computational capacity, they require specific conditions to produce the accurate details of a distorted signal. For instance, if the sampling frequency is not more than twice the highest signal frequency, it can lead to aliasing. The picket-fence effect can also occur when analyzing a non-integer multiple of the fundamental frequency [13]. Also, STFT can be used to find the components of the phase and frequency of any small part of the signal and, therefore, does not require the signal to be static. However, the STFT is not as accurate as the FFT. It is important to note that the time information of a distorted signal can not be obtained using DFT [19].

The wavelet transform can not be used to obtain an accurate amplitude and phase of the harmonic frequencies but to obtain information about the fundamental harmonic. The wavelet transform can also obtain the harmonic frequency component[20]. Another limitation of the wavelet transform is the spreading effect, which can result from the mother wavelet [19].

C. *Role of Computational Tools and Software for Harmonic Analysis*

Several software tools have been developed to analyze electrical power systems due to the increasing need for real-time analytical data. This data can be used to observe the system conditions and better predict how the system will react to various changes and system conditions. For this purpose, conventional methods can be tedious, time-consuming, and prone to computational error. Some of these software tools available have been used for harmonic analysis of power systems, and their results are compared with real-time data to test for accuracy.

One of the most common tools used by researchers, including [14], is MATLAB. MATLAB Simulink software tool was used to simulate a network with an active shunt filter for harmonic detection. [21] also used MATLAB to analyze and model a power system network consisting of an alternator, non-linear load and two passive filters to mitigate the harmonic content. MATLAB can also test for the effects of a newly proposed structure or equipment in the power system network. This was done by [22] for their proposed predictive smart impedance, which would be connected at the load side of the network. The system was effective at both load-side harmonics mitigation and reactive power compensation.

[18] succeeded at a modifying process using the Matpower tool for harmonic power flow analysis. This modification was also used to analyze a passive power filter. Matpower is a simulation package based on MATLAB. Another software tool used for harmonic analysis is dSPACE. [23] used the dSPACE software to simulate their proposed hybrid shunt active power filter for harmonics mitigation in the power system.[15] used the electromagnetic transient program (EMTP) and ATPDraw with MATLAB software to test their proposed grid protection mechanism. These software tools are useful for fast and efficient analysis of harmonic content in power systems and can be modified to suit specific requirements. Other software for harmonic analysis in power systems include NEPLAN**,** ETAP**,** PSCAD**,** Digsilent PowerFactory**,** PowerWorld Simulator**,** PSS/E (Power System Simulator for Engineering), SPLAN, PSCAD (Power Systems Computer Aided Design), and others are essential.

IV. Challenges in Sub-Saharan Africa's Power Systems

It is generally believed that the electrical power systems in sub-Saharan African countries are significantly below standard in infrastructure, personnel, and capacity. This section will discuss the challenges some of these countries face and the potential issues that could arise going forward, especially with integrating renewable energy sources.

A. *Characterization of Electrical Loads Specific to Sub-Saharan Africa*

To evaluate the power system in Sub-Saharan Africa, especially relating to harmonics, it is essential to discuss the types of loads typical to the people in the region and their usage patterns. This gives us an idea of what habits or behaviour are specific to the region. It is challenging to find a review of a wide area's load types and patterns, and certainly not of the region as a whole. This is due to the problems related to the accuracy of the data and sample size. For this purpose, some research done over a small sample size will reviewed for reference.

[24] assessed the load profile of the female hostels at Ahmadu Bello University, Zaria, Nigeria. This was

an attempt to find the energy consumption in these hostels. Using questionnaires, the study identified twenty-four (24) appliances prevalent in the hostels. Hot plates, heaters, lamps, refrigerators, mobile phones, laptops, fans, irons, and electric kettles were the most used appliances. The flatteners and hand driers contributed significantly to the energy consumption despite not being used as much as previously mentioned.

[25] identified twenty-one (21) electrical appliances as well as four (4) lighting devices that were primarily used in Ghanaian residential homes and sort to characterize the residential demand in Ghana. According to the study, refrigeration contributed 47% of the total household demand in 2015. In 2015, air conditioning contributed 12%, electric iron and washing machines contributed 5%, cooking appliances (cooker, microwave, and food processor) contributed 2%, and house cleaning and water heating appliances contributed less than 1% of the total household demand. The study then went on to predict the impact of these appliances by the year 2050. However, that is beyond the scope of this review.

[26] studied the load pattern of the Ayobo 2 Electric Power Distribution Area, Lagos, Nigeria. They identified some factors that determine power consumption at any particular time, including the season of the year, time of the day, day of the week, and the geographical location of the study. The load patterns were described using four categories.

- The working time spanned from 5 am, when residents of the area would start heading to their places of work, till 6 pm, when they would mostly be back to their homes. This period saw the daily peak at 3 pm when some residents and students returned to their homes to utilize household appliances for cooking and entertainment.
- The leisure time spanned from 6 pm, when most residents would return home, till 10 pm, when they would sleep.
- The sleeping time, usually between 10 pm and 5 am, is when the residents go to sleep for the day. Only some lighting and cooling appliances are expected to be operational during this period.
- Finally, there is the weekend load pattern when the residents usually don't go to work. This means the working and leisure periods would be different for this period of the week.

B. Limitations in Grid Infrastructure and Monitoring Capabilities

When discussing the limitations of the electrical system in Africa, specifically sub-Saharan Africa, some points are usually mentioned, including the following.

- Conflict.
- Oil prices.
- Natural causes.
- Poor investment [27].

[28] mentioned in their research that few studies have been done on analyzing the electricity demand of the sub-Saharan Africa region. The few they found to discuss the topic took an economic approach to the subject, ignoring other factors that could affect electricity demand in the region. This shows that there is little data available about the actual demand for electricity in the area. With this uncertainty, monitoring the capabilities of the grid becomes difficult. Similar issues are faced regarding infrastructure and equipment since the true demand in the region remains unknown.

[29] also mentioned the uncertainty faced in the monitoring capabilities of the distribution network in Ghana. This uncertainty led to discrepancies in the total energy consumed in certain regions.

Several researchers have noted that Nigeria's electrification rate is relatively low as the power generated is too low compared to its population. [30] quotes an electrification rate of 59.3%, while 40.7% suffer frequent electricity blackouts. A major reason is the low amount of electricity generated compared to the country's population. [30] found that a high transmission loss of 9% due to aging infrastructure in the country was another reason for the limited electrification of the country. Also, some regions, especially the Northern regions, lack the infrastructure to reliably transmit and distribute electrical power to the consumers compared to other areas like the Southern region.

C. Influence of Renewable Energy Integration on Harmonic Propagation

Sub-Saharan African countries have seen an imbalance in the electricity demand and supply increase, especially in Ghana and Nigeria. As the population and number of appliances increase yearly, the corresponding increase in grid capacity has been significantly lacking. For this reason, integrating renewable energy in the electric power systems is encouraged to close the gap between demand and supply of electricity. One of the most viable renewable energy options is solar energy using a distributed generation system. This, however, comes with its limitations not only in terms of cost but also in terms of power quality.

When integrated into the grid network, solar and wind systems use converters (inverters and rectifiers), which, as stated earlier in this review, are harmonic sources in the electric power system. Coupled with their varying output power, they can instead become significant sources of harmonics in the power system [31]. Solar and wind-generating systems were introduced using the DigSILENT PowerFactory software to simulate a network, and the resulting harmonic distortion was measured. It was found that the solar system contributed more harmonic distortion to the network, and the level of harmonics measured depended on the point of the network where the systems were integrated [31].

V. EVALUATION AND MEASUREMENT OF HARMONICS

It is crucial to evaluate and measure the harmonic content level in the system first to mitigate harmonic distortion generated in electric power systems. This will help to give a more explicit analysis of the harmonic content and its sources. After implementing the mitigation techniques, it would still be essential to monitor the harmonic content level to ensure it is kept below the standard level for the system.

A. Techniques for Harmonics Measurement and Data Acquisition

1) Power Analysers

One method for harmonics measurement involves the use of power analyzers. [32] described some of the required qualities of a good power analyzer. It should have the following.

- Its clock speed should be high.
- It should have high computational power.
- It should be able to store large amounts of data.
- It can be connected to the internet using Wi-Fi modules.

The basic circuitry of a power analyzer should also include the voltage measurement circuit, current measurement circuit, frequency measurement circuit, communication circuit, and circuit for power supply. [32] used FFT to analyze the distorted signal. The power analyzer designed during their research measured harmonic content up to the 50th harmonic reliably. However, it is important to calibrate the power analyzer properly when using power analyzers. [33] described a phenomenon of spectral leakage that can occur when the measurement window is not adjusted appropriately. Spectral leakage can affect the accuracy of measurement carried out on the electrical power system.

2) Smart Meters

Since the distribution network generates a significant level of harmonic content in the power system, smart meters have been considered a means for measuring the harmonics generated by the distribution network. Smart meters offer a cheaper and more effective method for evaluating the harmonic content generated in the power system [34]. Smart meters provide wide-area measurements taken at different points of the network. This can help further analyze the network to determine the harmonic content generated at those different points. In their work, [35] proved the smart meters' accuracy in measuring harmonic content by modelling household loads in a testbed laboratory. However, there were accuracy concerns about smart meters when subjected to voltage distortions at higher harmonics.

B. Case Studies From Sub-Saharan Africa on Harmonic Assessment

Research has been done in sub-Saharan Africa to measure and evaluate harmonic distortion in the electrical power system. [9] for instance, researched to analyze and assess the harmonic content in the Nigeria power grid. The research, however, was carried out using the ETAP software tool rather than real-time measurements. Similarly, a lot of other research involves using software tools for harmonics analysis. Therefore, only a handful of research studies have used measured real-time values in the region. [36] in Ghana, used the power quality analyzer to measure and analyze harmonics generated due to integrated PV systems in Kwame Nkrumah University of Science & Technology (KNUST). In their research, [37] used the C.A. 8335 Power Quality Analyzer to analyze and evaluate the harmonics generated by domestic household appliances. Measurements taken at the point of common coupling closest to the domestic consumers indicated high harmonic content generated. In the department of Aminu Kano Teaching Hospital, Nigeria, the effects of harmonics on crucial medical equipment were observed, and possible mitigation techniques were discussed and developed by [38]. Using the power quality analyzer and MATLAB software, a satisfactory method was developed to ensure the safe operation of the equipment in the hospital. [39] developed a smart meter for monitoring the consumer side of the grid to efficiently track the power quality conditions of the supply to each household.

C. Challenges Related To Data Accuracy, Availability, and Reliability

Data's accuracy and reliability are crucial concepts that determine how useful the data can be for the purpose it was gathered. The more accurate and reliable a dataset is, the more inference or evaluation processes can occur. In the case of harmonics measurement and evaluation, it means the harmonics in the system can be better tackled and its effects better reduced in the system using various mitigation techniques.

Some challenges highlighted by [40] include the following.

- The accuracy and reliability of the measured signals could be affected by noise.
- Real-time measurement of the power system signals demands a high computation capability since it constantly changes with time.
- The size of the data accumulated will be very large.

Another vital challenge or cause for the unreliability of data is due to the security concern of the measurement system [41] Smart meters are especially required to transmit the data gathered regularly and can be subject to cyber-attacks. If this concern is not properly addressed, the data collected can not be reliable or considered accurate.

Other challenges discussed by [42] include the following.

- The measurement devices, like the power quality analyzer, need to be calibrated to provide accurate measurements, and this calibration process is usually performed in accredited laboratories. However, these calibrations do not always cover all the possible readings for which the device could be used. The research stated an example of the calibration of phase angle. The calibration process also does not involve peripheral devices like the test boards.

- Errors can occur due to heat generated by the measured system, which can cause noise. The system's thermal stability must be considered before
- the measurement is carried out to ensure the accuracy of the measured data.
- Cable impedance is also a factor to consider when determining the accuracy of data obtained. A simple experiment by [42] using different cable lengths and LED lamps, showed the different harmonic values obtained due to the different cable lengths.

VI. Impacts of Harmonics on Power Quality and Equipment

Harmonics in the electrical power system negatively affects the operation of the system and can cause damage to the equipment in the system. Some of the impacts of harmonics will be discussed in this section.

A. *Effects on Transformers, Motors, and Other Critical Infrastructure*

Different equipment in a power system will be affected differently by harmonics depending on their mode of operation. Transformers are usually the most affected in a power system, along with capacitor banks used for power factor correction [43].

1) *Effect on Transformers*

Transformers in a power system are one of the most vital equipment and also one of the most delicate equipment. They require utmost care and must be operated at their specified rating for effective functionality in the system. However, harmonic content in the system can cause a deviation from a normal system where the transformer operates at specified conditions. Therefore, the effects of this on the transformer need to be studied.

- The transformer's core can become saturated.
- It can lead to increased power losses in the transformer due to hysteresis and eddy current losses.
- The efficiency of the transformer is reduced due to increased losses.
- It can lead to a decrease in the transformer power factor.
- The temperature of the transformer is influenced by the temperature of the winding, transformer oil, cleats, insulation, and leads. Harmonic distortion in the syste can lead to the overheating of the transformer as previously discussed.
- It can lead to the eventual failure of the transformer due to the transformer tap changer and bushings being put under excessive stress.
- The transformer's life expentancy is eventually reduced due to being under constant excessive stress [44].

2) *Effects on Motors*

The impact of harmonics can be seen in induction motors and an experiment was carried out to demonstrate it. An induction motor was connected to power supply containing harmonics and its behaviour was observed. It was found that the motor experienced additional losses due to the harmonic distortion, mostly caused by the low order harmonics [3].

[3] also categorises the impact of harmonics in three ways. The effects of harmonics can be seen in industrial facilities especially petrochemical factories where power quality issues, usually observed from the point of common coupling (PCC), can negatively impact the operation of the various equipment used and thereby leading to production loss.

The effect of harmonics can also be seen in distribution networks where utility companies are finding it difficult to improve the power quality to the accepted standards. This is majorly due to the fact that more non-linear loads are connected to the network, leading to relatively high harmonic distortion at various points in the system.

B. *Potential Risks of Harmonic Resonance in Poorly Maintained Grids*

Resonance generally leads to the amplification of harmonics in the electrical power system and is an important aspect of harmonics analysis. Some filters designed for mitigating harmonics may end up causing resonance in the system, thereby having the opposite effect. When designing these filters, it is vital to consider the resonance effect of the proposed filter. Also, in microgrids, an increased number of distributed grids, unbalanced loads and non-linear loads can amplify the effects or impact resonance in the system [45].

[46] in their research work found that the power factor compensation system used in industrial networks and some distribution networks can cause a significant amplification of the harmonics in the power transformer of the system due to resonance effect. The paper even states that it could be preferable to not integrate such power factor correction system in favour of avoiding the harmonics injection that would occur otherwise.

The risk of resonance in a system is the amplification of already existing harmonics to levels that could significantly damage the equipment in the system. The tripping of relays and circuit breakers become a lot more frequent and the overheating and eventual failure of the transformer will be observed.

[45] proposed an active damping method in order to compensate for the resonance in the microgrid system. The proposed method was designed to be easy to for implementation, able to consider uncertainties in some system parameters as well as variations in the frequency, and keep the dynamism of inner control levels.

C. *Economic Impacts of Harmonics*

The economic impacts of harmonics on the electric power system can be observed in different ways in the power system. Failure of equipment in the power system can be as a result of over voltage or under voltage due to harmonics. Harmonics can lead to the reduction of the equipment life expectancy and it therefore would need to be replaced sooner than expected. Other economic impacts of harmonics according to [47], are discussed.

- Voltage harmonics can cause significant reduction in productivity.
- Equipment become less effective and losses become increased.
- It increases the cost of repairing the equipment since it becomes prone to constant damage.
- Safety concerns.

One of the major challenges to determining the true extent of the economic impact of harmonics is the numerous harmonic orders that exist in the distorted signal. Since they each can have different effects on the equipment, it becomes more difficult to estimate the true impact of the harmonic content.

The malfunctioning of equipment in the power system, especially in higher voltage levels can lead to system downtime which affects the country or region's economy. Similar effect is observed when the relays and circuit breakers trip due to the effect of harmonics in the system [47]. The economic impacts can include the following.

- Cost of restarting the system.
- Utility costs incurred as a result of the system downtime.
- Production losses.
- Cost of repair.

Due to the effects of harmonics in the power system, researchers are looking for more cost-friendly mitigation techniques but mitigating harmonics over a wide area will incur significant cost. [48] proposed a detuned filter in place of capacitor banks for networks with low harmonic content and combination of detuned and tuned filters for networks with high harmonic content. However, the financial payback period for the detuned filter is 1.6 times longer than the financial payback period of the capacitor bank.

VII. Mitigation Strategies and Solutions

The major focus for researchers today is to find effective and cost-friendly methods to mitigate harmonics in electrical power systems. The aim of these methods is to reduce the harmonic content in the system to a level acceptable and less likely to cause damage to the system and equipment as discussed earlier.

A. Harmonic Filtering Solutions

The most discussed solutions for harmonics in the power system today involve filters, active and passive filters. The major aim is to separate the harmonic frequencies out of the system and allow only the fundamental frequencies in the system. Since the low order harmonics are known to cause the most damage, most of the research into mitigating harmonics are focused on mitigating low order harmonics.

1) Passive filters

They are generally used for mitigating harmonic content generated by industrial loads and are known for their high efficiency and being relatively cheaper. Compared to the other filter designs, the passive filter requires less maintenance. The different types adapted according to [49] are the following.

- Single tuned passive filter.
- Double tuned passive filter.
- High-pass passive filter.
- C-type passive filter.

Due to the low impedance path provided by the single tuned passive filter compared to the other types, it is the more commonly used. The single tuned filter also contributes reactive power to the network and it is cheaper and reliable. The high-pass and C-type passive filters are mostly used for absorbing high order harmonics.

[49] described a single tuned passive filter as one consisting of a capacitor and an inductor which aims to provide a low impedance path at the target frequency.

However the passive filters can have the following limitations or disadvantages [50].

- They can be limited by the tolerance of the L-C components.
- They can become overloaded when exposed to more harmonic content than they were designed to handle.
- They can be affected by the supply impedance.
- Their components can be bulky.
- They can cause resonance in the system.

2) Active Filters

Active filters use power electronics components in order to reduce the harmonic content in a network. The active filter works by generating a signal aimed at canceling out the harmonic content in the original signal. For this purpose, information about the harmonic content in the network is required so as to generate the appropriate canceling signal [50].

Unlike passive filters, active filters do not cause resonance in the network, they are not bulky, and their performance does not depend on the network properties. Its disadvantages are the following.

- It can cause noise due to the switching of the power electronics components.
- It can cause electromagnetic interference.

The types of active filters are shunt, series and hybrid active filters. The most common type is the voltage source inverter shunt active filter since it is easy to understand and install. The series active filter is connected in series using a matching transformer. The series active filter injects voltage harmonic signal into the network through the transformer and the injected signal is added to or subtracted from the distorted signal in order to produce a pure signal.

3) Hybrid Filters

The hybrid filter aims to combine the benefits of both the passive and active filters in order to provide optimum results and totally mitigate the harmonic content in a network. Therefore, the hybrid filter both eliminates a target harmonic frequency and also generates a signal in order to cancel out the harmonic content in the network.

[51] applies a hybrid filter to mitigate the harmonic content in a wind power plant. It was found that the harmonic content of the system was significantly

reduced while avoiding the generation of resonances in the system.

B. Design Considerations for Harmonics Mitigation in Grid Modernization

When designing a harmonic mitigation system in a network, it is always important to start by analysing the network in order to determine the condition of the network and its load pattern. Analysing the network also helps to determine the type of mitigation system to be employed for that network. It is also here that the harmonic sources present in the network are identified.

Another design consideration is harmonic resonance in the network. If not carefully considered, the mitigation system may only amplify the resonance in the network.

Other design considerations include the following.

- Reactive Power Compensation: power quality issues can also be as a result of reactive power in the system. Harmonic filters can also function as reactive power compensation, as discussed earlier in this paper, in order to provide quality power supply to the consumers [52].
- Restriction on Damped Time Constant: in order to prevent amplifying the harmonic content, the filters must be inductive compared to the harmonic signal in the network [52].
- Harmonic Requirements: when designing a harmonic mitigation system, the requirements or standard for harmonic distortion in the network. This is the harmonic content level determined to be relatively harmless for the network and should be adhered to strictly [52].
- Environment and Ageing Effect: the effect of the environment on the components to be used would need to be considered as well, to ensure the mitigation system is operational for a considerable period of time.

C. Regulatory Standards for Harmonics in Sub-Saharan Africa

Everywhere in the world, there exist some regulatory standard that aim at guiding grid operators on the acceptable level of harmonic content at every voltage level in the power system. It makes analysing the power system easier since there is a specified level that must not be exceeded. Even in Sub-Saharan Africa, regulatory standards exist in order to ensure that the power quality in the power system is not compromised.

The IEC61000 is the major regulatory standard employed in the Sub-Saharan African region. The different part of the IEC61000 standard is discussed.

- IEC61000-3-6, according to [53] defines harmonic emission and sets standards for harmonic emission level generated by harmonic load sources.
- IEC61000-4-30 sets a standard for power quality measurement devices such that harmonic measurements carried out on different networks at different time and places can be compared. Similarly, when these instruments are connected to the same network, under the same conditions, they should give similar results [54]. The standard defines two classes for harmonic measurement, class A and class B. Class A instruments are mostly used in cases where there is uncertainty, usually between consumers and the utility providers. However, class B instruments are used where uncertainty is not considered, like when troubleshooting or taking surveys of the system for documentation purposes [55].
- IEC61000-4-7 defines the measurement standards for harmonics and interharmonics [54].
- IEC61000-4-15 describes the standards for measuring flickers in a power system using power quality measurement devices[54].
- IEC 61000-3-2 defines the limits of harmonic currents that can be allowed into the power system by electrical equipment at voltage levels higher than 220 V and per phase current greater than 16 A. This standard provides limitations for the second to the fortieth harmonic [56].
- IEC 61000-3-12 applies to electrical equipment that are connected to the power system at low voltage levels of 220 V and per phase current of 16 A. It also aims to limit the harmonic currents generated by such equipment [56].
- IEC61000-2-1 describes disturbances in an electromagnetic environment for frequencies up to 10 kHz [56].
- IEC61000-2-2 describes compatibility levels for frequencies up to 9 kHz [56].
- IEC61000-2-4 describes compatibility levels for industrial loads in the low or medium voltage levels and low frequency range [56].
- IEC61000-2-6 is concerned with the distortion generated in the power supply network of industrial loads [56].
- IEC61000-2-8 describes voltage fluctuations and tripping in the power supply system [56].
- IEC61000-2-12 describes the compatibility levels for distribution supply network at frequencies up to 9 kHz and voltage level between 1 kV and 35 kV [56].

VIII. Future Outlook and Recommendations

The future of the power system looks really exciting considering the number of new innovations and research work being published. Of course there will always be more that could be done, but there is hope that researcher will work to find the best methods to solve the problem of harmonics by implementing the following

A. RECOMMENDATIONS

1) Awareness and Advocacy

Recognizing the impact of non-linear loads like laptops on power quality can promote responsible usage and support manufacturers who prioritize energy-efficient designs.

2) Design and Control Strategies

- Harmonic-Aware Design: Researchers can explore power electronics design principles that minimize harmonic generation at the source. This can involve optimizing switching techniques and component selection in equipment used within research labs.

- Demand Side Management (DSM): Implementing smart control systems for research equipment can help manage power consumption patterns and potentially reduce peak harmonic currents. Researchers can investigate intelligent scheduling or staggered operation of equipment to minimize simultaneous high-harmonic loads.

3) *Monitoring and Analysis*

- Harmonic Monitoring: Implementing power quality analyzers in the sub-distribution network allows researchers to continuously monitor the harmonic profile and identify problematic areas. This data can be used to assess the effectiveness of mitigation strategies and guide further research efforts.
- Harmonic Modeling and Simulation: Researchers can develop computer models of the university's power network to simulate different harmonic mitigation scenarios. This allows for a more informed and cost-effective approach to implementing solutions.

B. *Emerging Trends in Harmonics Mitigation*

One of the trends is related to smart grid technologies being researched on for implementation in electrical power systems. The smart grid technology enhances communication within the grid and allows for measurements to be taken at different points in the network using digital IoT devices. As discussed by [57], smart grid technologies help to improve the reliability and quality of power supply and helps to monitor the different stages in the network. Similarly, [58], carried out a research to show how harmonic distortion can be measured in the consumer side of the network in order to accurately determine the major harmonic sources and also how different mitigation techniques like load shifting affect the harmonic content generated.

The application of artificial intelligence is also a notable trend in harmonics mitigation as the need for measuring and mitigating harmonic distortion increases. A major advantage of artificial intelligence is its ability to learn from the past data fed to it and thereby using that data to predict the harmonic content in the network. [59] reviewed how the different artificial intelligence techniques could be used to learn the network characteristics and patterns, predict future events of harmonic distortion based on available data, and identify and analyse harmonic sources in the network. The techniques discussed include machine learning techniques using supervised, semi-supervised, reinforced, and unsupervised learning, artificial neural network (ANN), 2D convolution neural networks (CNN), recurrent neural network (RNN), long short-term memory networks (LSTM), and support vector machine.

C. *Government Policy Recommendations for Harmonics Management in Developing Regions*

The government plays a very vital role in enhancing the management of harmonics in the electrical power system. Government policies can help to encourage the use of electrical equipment and appliances that operate within the IEC61000 regulations. The use of smart meters for the measurement of power quality and harmonics at the distribution stage can also be encouraged, thereby enhancing smart grid technology. Some of the recommended polices include the following.

- Public awareness of harmonics, its sources, and effects in the electrical power system.
- Regulatory frameworks should be provided for the use of electric vehicles.
- Promote the use of filters for mitigating harmonic distortion in the electrical power system.
- Establish a training programme for engineers and technicians so that they can better understand and handle harmonic distortion.
- Support research on harmonic distortion and its mitigation techniques.

D. *Research Gaps and Areas for Future Investigation in Sub-Saharan African Power Systems*

The areas for future investigation in Sub-Saharan Africa are discused.

- Few research works in the Sub-Saharan Africa region have focused on utilisation of software tools for harmonic filter optimization [60]. Harmonic filters are still being developed and research on them is still ongoing. The use of software tools, that have been discussed earlier in this paper, like MATLAB and ETAP to design more efficient and cost efficient filters should be adopted by more researchers in the region.
- In order to enhance the ability of researchers to carry out research on harmonic filters using software tools, it is important to be able to appropriately model different networks along with the equipment and harmonic sources connected in the network. An accepted model for these equipment need to be developed to aid further research in the field.
- In Sub-Saharan Africa, there is an increase in the number of renewable energy systems owing to the poor power supply in the region. The effects of these renewable energy systems however need to be studied in order to guide this rise appropriately and manage their harmonic content generation.

IX. CONCLUSION

Harmonics in the electrical power system has become one of the major topics being discussed by researchers all over the world and in Sub-Saharan Africa where power quality has been a significant probem in recent years. As the population in the region continue to grow and the demand for more power efficient electrical appliances grow, the more profound the effects of harmonics become in the power system. The sources of harmonic distortion have been identified as majorly non-linear devices and equipment in the power system, including distributed generation systems and renewable energy systems. The effects of harmonic distortion have also been discussed, reiterating the findings of research work on these effects.

It is important to further research on the measurement, analysis, and mitigation of harmonic content in the power system. To mitigate the effect of harmonic distortion in the region, engineers and technicians need to be trained and educated on the effects and sources of harmonics, the IEC61000 standards related to harmonic distortion, and the mitigation techniques available due to research work done on them. The government of the countries in the region also have a role to play in implementing policies that support the research in harmonic distortion and mitigation techniques, and also implementing these mitigation techniques in the region.

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