Harmonic injection of domestic nonlinear loads in Ghana's power distribution system: analysis and mitigation using a low-cost notch filter

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Abstract
Due to global efforts to save energy, digital light processing (DLP) and direct view televisions (DVTVs) are being replaced by energy-efficient liquid crystal display (LCD) and light emitting diode (LED) televisions. However, these energy-efficient appliances cause harmonics to be injected into the power distribution system, posing a threat to power quality. This study investigates the harmonics generated by common domestic appliances, particularly LCD and LED TVs used in homes in Ghana. Field harmonic measurements were taken using a C.A. 8335 Power Quality Analyzer at a selected facility and were then replicated in a simulation using MATLAB/SIMULINK to model the facility's area network capacity of 100-kVA, 11kV/433V. The study proposes a notch filter as a harmonic mitigation technique, which is integrated into the simulation design and found to be effective at reducing total harmonic distortion current to 0.05 % when applied in parallel to nonlinear loads. The study also compares the harmonic distortion generated by LED TVs and LCD TVs, finding that both types generate high levels of distortion.

Keywords: Harmonic Current, Harmonic Voltage, Notch Filter, Total Harmonic Distortion, Power Factor, Transformer

Introduction
With a growing knowledge of energy efficiency, DVTV has been described as being an energy guzzler. As a result, people all over the globe have gradually replaced these DVTVs with LED and LCD TVs (Jabbar et al., 2008). LED and LCD TVs are proven to be much more energy-efficient and last longer than DVTVs. However, the production of these energy-efficient TVs, especially LED and LCD TVs, was initially met with outright rejection because their introduction into the power systems would increase the total harmonic distortion (THD) (Parsons, 2006). These appliances are made of non-linear solid-state components, such as diodes, rectifiers, transistors, and switches (Korovessis and Vokas, 2004), which are well-known to be harmonic sources in the power distribution system (Verderber et al., 1991). The switching techniques used to control them can act as a nonlinear source. The effects of harmonics in a power system are technically manifested as line current and voltage distortions. Harmonic effects in the power system include, among other things, repeated tripping of protective equipment, high neutral-to-earth voltages, reading errors in energy meters, and transformer overheating. Previous research indicates that harmonics in the power distribution system have led to an 96 per cent rise in distribution transformer technical losses in the Electricity Company of Ghana (ECG) distribution zones in 2017 (George and Kingsford, 2017). In the ECG operation zone, the cost of energy per year resulting from the harmonic losses is found to be (GHS 2,220,395.11/year) (USD 555,098.78/year) (George et al., 2011). There are commercially available harmonic mitigated devices, however, the cost of commercial active and passive filters is very high. For instance, the current price of a three-phase active harmonic filter is $899.00 - $2,269.00. Also, the Tyco 3EMC1 power line filter, which is a very low-cost filter is $17.11. A three-phase Mild Steel PHF Passive Harmonic Filter is also sold at $2406.97. All these are very expensive which increases the overall cost of quality power distribution.

Many electronic appliances have evolved as a result of recent technological advancements and the need to meet client requests. TVs are one of these changing technologies, which have replaced cathode ray tube (CRT) technology with LCD and LED. In addition, considerable changes in the lighting load also occurred in recent years, with countries prohibiting the sale of classic incandescent light globes as a demand reduction approach (Elphick et al., 2010). The overall supply current will include harmonics when two loads (linear and nonlinear) are coupled and fed by a sinusoidal source thereby resulting in power quality issues (Azevedo et al., 2009; Arrilaga and Watson, 2003). An investigation of modern domestic appliances to determine their input current characteristics with regard to their varying supply voltage conditions was conducted (Ghorbani and Mokhtari, 2015; Elphick et al., 2010). The appliances examined were chosen based on a mix of penetration levels and power consumption magnitudes. These appliances they examined are expected to be found in the majority of households or are representatives of other appliances with high power demands, posing a greater risk to the electrical distribution network. Waveform and displacement power factors influence harmonic magnitudes and phase angles, particularly higher frequency harmonic phase angles. The net harmonic currents generated by 10 or more surrounding harmonic loads are not completely additive due to natural phase cancellation.

Despite these well-known issues with nonlinear loads, Ghana has had to embrace these appliances to reduce the power demand by its consumers. Ghana’s energy sector has suffered several crises in the energy sector leading to its low energy production-to-demand ratio. As a result, Ghanaians over the last decade have imported thousands of these Energy efficient TVs into the Country. In addition, shareholders in the energy sector saw these appliances as a way of conserving power and meeting the energy demand. Currently, power generation in the energy sector has improved tremendously due to the measures being put in place by stakeholders. Some of these measures include the embrace of renewable energy such as solar, wind, and biomass.

The key contribution of this research is to evaluate the harmonic injections into the power distribution system by LED
and LCD TVs, and design a harmonic rejection notch filter to notch out high-frequency components, particularly 3rd harmonic components. To achieve this, we propose the integration of a notch filter into the power distribution network. Using MATLAB Simulink software, we modelled and simulated the distribution network with the nonlinear load models and notch filter.

Materials and Methods

Harmonic generation and analysis

The harmonics of nonlinear appliances as investigated in the majority of studies recorded in the literature were either by taking measurements of their harmonic characteristics in laboratory installations or by experimental setups. The presences of harmonics typically change the shape and structure of the fundamental current and voltage signals from the pure sinusoidal wave patterns at the fundamental frequency. This type of deviation, known as harmonic distortion, is undesirable in the operation of the power system for a variety of reasons as indicated in the introduction (McLornet et al., 2019). The fundamental frequency ($f_o$) is represented by harmonic components as an integer. The second to the nth harmonic components are expressed as $2f_o, 3f_o, 4f_o, \ldots, nf_o$. In a case of a 50 Hz AC power supply such as in Ghana, $f_o=50$ Hz. In addition, the second to nth harmonic components are generated as products of the fundamental frequency as in $2\times50$ Hz, $3\times50$ Hz, $4\times50$ Hz, $\ldots, n\times50$ Hz. The third (150 Hz), fifth (250 Hz), seventh (350 Hz), and ninth (450 Hz) current harmonics alter the clean sinusoidal waveform of the fundamental current flowing at 50 Hz frequency. The transmission and distribution of power between the generators and the load point is the point of concern for harmonic distortions (IEEE, 2014). Using the concepts of an equivalent current source and the superposition of individual harmonic components, it is possible to demonstrate how harmonic currents flow through the supply system and can lead to induced voltage distortion at a specific point on the network (Elphick et al., 2010; Raymond et al., 2020; Raymond et al., 2021). This distortion is usually measured as the Total Harmonic Distortion (THD) voltage and current. The total harmonic voltage and current distortions are expressed in several pieces of literature (Jabbar et al., 2008; Parsons, 2006) as Equation (1) and (2)

\[
THD_v\% = \frac{\sqrt{I_2^2+I_3^2+I_4^2+\ldots+I_n^2}}{I_1} \times 100 = \left(\frac{\sqrt{\sum I_n^2}}{I_1}\right)^2 \times 100
\]

\[
THD_i\% = \frac{\sqrt{I_2^2+I_3^2+I_4^2+\ldots+I_n^2}}{I_1} \times 100 = \left(\frac{\sqrt{\sum I_n^2}}{I_1}\right)^2 \times 100
\]

From this, the power factor (PF) is obtained as the product of the DF and DPF giving by Equation (5):

\[
PF = \frac{\cos \phi}{1+THD_i^2}
\]

If phase angle variability is not taken into consideration, system models will predict exaggerated voltage damage levels. The net addition, or diversity factor, for the third harmonic, is unity, while it decreases for higher harmonics.

Load connection approach

The system impedance and load connection as depicted in Figures 1 and 2, which can be used to readily characterize harmonic voltages and harmonic current flow. For multiple households, a single household, and a single user load scenarios. The points of common coupling (PCC) are chosen to be at the transformer side, the feeder to the building, and the meter, respectively as depicted in Figure 3.

Load measurement

The selected facility for carrying out the harmonics measurement is a domestic building with a 2 km 11 kV overhead line from a local district power station making up the regional power network system. The overhead cables are installed horizontally and evenly spaced at 90 cm intervals which supply power to the area’s 100 kVA (11/0.433 kV delta/star) transformer supplying 3-phase, 4-wire pole-mounted distribution lines. Also, the three-phase, four-wire circuits are vertically mounted on a pin insulator and spaced 30 cm apart with a distance of approximately 38 m between the poles. Additionally, the region covered by the radial distribution line is approximately 0.9 km by 0.4 km square. A 120 mm² All Aluminum Conductor (AAC) is also used in the lines. A single-phase line is connected from the 3-phase 4-wire radial wires to the designated facility using a 6 m by 25 mm² AAC-PVC insulated single-phase line is used. Figure 3
gives a pictorial view of the facility's connectivity. Possible points of common coupling are indicated as PCC1 to PCC5. The PCC4 is at the pole where the domestic building supply was connected. Since PCC5 is the closest point to the consumer, the field harmonic measurement of the devices was taken at that point. The load for the measurement was placed in two rooms due to the fact that one of the LED TVs was already mounted on a wall and connected to a DSTV decoder. However, the DSTV decoder was turned off. The measurement setup included one LED Samsung TV, one LED Philips 40 inches TV, One ViewSonic LCD monitor, and one LG LCD TV as shown in Figure 4.

The loads’ selection for the measurements was done to represent the largest fractions of residential and commercial or industrial feeder loads that include modern devices. The selected loads’ combinations were subjected to large (-25 to -75 %) voltage changes in slow ramps and sudden steps. For smaller loads, several devices were tested in parallel to produce one composite load. The measurement step-ups were done with respect to the IEEE Working Group on Load Representation for Dynamic Performance. In addition, the loads were operated in their normal conditions throughout the tests. Also shown in Figure 5 is the power quality analyzer indicating all the probe connections.
**Notch filter design**

The majority of big power (usually three-phase) electrical nonlinear devices frequently require mitigation equipment to keep harmonic currents and accompanying voltage distortion below acceptable ranges. Depending on the desired solution, mitigation may be provided as an inherent element of nonlinear equipment such as an AC line reactor or a line harmonic filter for AC PWM drive, or as a distinct piece of mitigation equipment, for instance, an active or passive filter linked to a switchboard. Harmonics can be reduced in a variety of methods, ranging from variable frequency drive designs to the installation of auxiliary equipment.

Harmonic distortion in power distribution networks can be reduced using one of two methods: passive or active filters. Passive filtering is the most basic conventional approach for reducing harmonic distortion (Raymond et al., 2020; Raymond et al., 2021). This work uses an LC notch filter to filter out harmonic components occurring at higher frequencies (2nd to 7th). The schematic of the proposed LC notch filter is given in Figure 6.

Considering measurement findings revealed very strong second and third harmonics, an LC resonator was used with the necessary resonance at 2fo to 7fo to filter these strong harmonic components. The filter resonance analysis is given in equation Eqn (6) while the LC resonator’s impedance (Zf) with a finite quality factor (Qf) of the inductor is given in Eqn (7) (Raymond, 2020).

\[
Z_f(s) = \frac{1}{sC_f} / (R_f + s \cdot L_f)
\]

(6)

\[
Z_f(s) = \frac{R_f \left(1 + s^2 L_f / R_f\right)}{s + \frac{1}{\omega_f Q_f}} = \frac{R_f \left(1 + s^2 L_f / R_f\right)}{1 + \frac{1}{Q_f \omega_f} \cdot \frac{s^2}{\omega_f}}
\]

(7)

Where \( R_f \) is the series resistance caused by the inductor's finite \( Q_f = \frac{s \cdot \omega_f L_f}{R_f} \) and \( \omega_f = \frac{1}{\sqrt{C_f L_f}} \) is situated at the third harmonic frequency. The effective impedance (Z) displays two separate characteristics for the acceptable fundamental frequency and unwanted 3rd harmonic frequency range as indicated.

**Simulink model**

Simulink is an interactive system for modelling complex nonlinear networks and is a complementary tool to MATLAB. It is a graphical, mouse-driven tool that allows you to simulate nonlinear, continuous-time, discrete-time, and hybrid systems by sketching a block diagram on the screen. Block sets are Simulink add-ons that provide extra block libraries for particular applications such as communications, signal processing, and power systems. Real-Time Workshop is software that generates C code from block diagrams and runs it on various real-time systems. The complete Simulink models of the system are shown in Figures 7 and 8 with and without the LC notch filter.

**Results and Discussion**

Several nonlinear devices were considered in the measurement. These included one 40 inches LED Philips TV, one 32 inches...
LED Samsung TV, one View Sonic LCD monitor, and one LG LCD TV. Despite using a limited number of nonlinear devices, the harmonic analysis can lead to an appreciable understanding of the effect of several nonlinear devices on the power distribution system. In addition, the maximum load can be obtained using simulation; however, that is out of the scope of this research work. The first field measurement included a parallel connection of one 40 inches LED Philips TV, one 32 inches LED Samsung TV and a sixteen-inch LED HP Pavilion core i5 laptop. The key objective of this research is to ascertain the impact of LED and LCD TVs harmonics on domestic installation systems. However, the power quality analyzer requires a computer connection to be able to transfer the measurement data for further analysis. This necessitated the use of the laptop in this case, which unfortunately did not have a functional battery and therefore needed to be connected to the measurement setup. To be able to decouple the THDs of the personal computer from the overall measurement results, an initial measurement was taken for only the personal computer. Figure 9 show the measured THDi and THDv of the sixteen-inch LED HP Pavilion Core i5 laptop. As expected, the results exhibited a strong harmonic current magnitude at the odd harmonic frequencies compared to the even harmonic frequencies. The THDi current was obtained to be about 24 %. The harmonic voltage magnitude was recorded as zero at the even harmonic frequencies as shown in Figure 9.

The measured THDi and THDv results of the LED TVs including the personal computer are reported in Figure 10. The results exhibited harmonic content from second to twelve. Interestingly, the second harmonic was significantly high compared to the third. The measured THDi was recorded as 80 %. The addition of harmonic content is not direct algebraic addi-
tion, as such the THDi of the personal computer can not be subtracted directly from the LED TVs.

Similarly, the measured THDi and THDv results of the LCD TVs including the personal computer are reported in Figure 13. The results also exhibited harmonic content from the second to the fifteenth. Interestingly, the second harmonic was significantly high compared to the third. The measured THDi was recorded as 82%.

To mimic a domestic setting of how TVs are used, a combination of LED and LCD TVs were connected at the same simultaneously as nonlinear load and measured. The harmonic contributions recorded are plotted in Figure 12. The harmonic current magnitude was recorded as high as 90% of the fundamental magnitude. This was almost double the third harmonic magnitude. The results also demonstrated the presence of harmonic content as far as the forty-ninth component which was about 30% in magnitude compared to the fundamental.

A real-time harmonic measurement was conducted. This was done by allowing the measurement setup for the various load combinations to run over a period whiles observing the measurement results. Figure 13 shows the percentage of the THDi for the cases of LED + personal computer as nonlinear loads, LCD + personal computer as nonlinear loads, and with the combination of the LED and LCD TVs connected at the

Figure 10 Measured harmonic (a) current and (b) of LED TVs

Figure 11 Measured harmonic (a) current and (b) voltage of the LCD TVs

Figure 12 THDi of a combination of two LCD TVs, two LED TVs and one laptop computer
The combination of the LED and LCD gives a higher overall THDi compared to every single case. To demonstrate the validity and effectiveness of the proposed low-cost notch filter, the entire measurement network was modelled in Simulink and simulated. The simulation was conducted with and without the LC notch filter. Figure 14 gives the simulation results without the harmonic filter. The results showed a distorted THDi waveform as evident in Figure 14. The total THDi was recorded as 54.21% excluding the personal computer harmonics. When the LC filter was connected, the THDi was reduced to 0.05%. Also, the waveform was improved into a pure sinusoidal waveform as shown in Figure 15. This demonstrates the effectiveness of the low-cost harmonic rejection filter in the mitigation of harmonic content in a power distribution network in Ghana.

**Conclusions**

This research work examined the harmonics of common domestic appliances particularly LCD and LED TVs used in Ghanaian homes. Field harmonic measurements were taken with a C.A. 8335 Power Quality Analyser at the selected facility. In addition, the facility area network capacity of 100-kVA, 11kV/433V was modelled in MATLAB/SIMULINK where the obtained field harmonics measurements were replicated in the simulation. Furthermore, an analysis of harmonic mitigation techniques was conducted. A notch filter was proposed, designed, integrated into the Simulink design, and simulated.

The measurement results of two LED and LCD TVs indicated a total harmonic distortion current of about 80% and 82% respectively. These included the harmonics generated by the personal computer that was connected. A comparison of the LED TVs and LCD TVs was conducted. The simulation results...
also demonstrated similar behaviour with a total harmonic distortion current of about 54% excluding the personal computer. When the LC notch filter was applied in parallel to the nonlinear loads, the total harmonic distortion current was reduced to 0.05%. This demonstrated the effectiveness of the proposed low-cost harmonic notch filter. The results of this work showed that large-scale use of the energy conservation televisions such as LCD and LED televisions has a negative influence on the power distribution system. This, however, can be reduced when low-cost filter devices are connected in parallel with the nonlinear load. This can be done either during power installation or by a consumer as a protective device.

Since network capacity varies, similar studies could be undertaken in Ghana in different locations in the remote regions where long radial 11kV lines supply consumers. With the use of more electronics loads in buildings these days, further studies could be extended to cover other non-linear loads such as scanners and printers in combination with televisions. Street LED lamps, which are now being promoted in Ghana power distribution systems, could also be considered for further studies, particularly their ageing effect due to harmonics.

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Conflict of Interest Declarations
The authors declare no conflict of interest.

References


