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Techno-Economic Analysis of Harmonic Disturbances in a University Environment - A Case Study at the University of Cape Coast

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Abstract: This research investigates the adverse impact of harmonic disturbances present in distribution substations on the electrical installations and distribution network of the University of Cape Coast in economic terms. Power quality analyser using the "very-short time" monitoring duration and referenced against the IEEE 519-2014 harmonics standard was employed to obtain both the voltage total harmonic distortion (THD_V) and current total harmonic distortion (THD_I). The average total harmonic distortions measured on the university was 16.43% with dominant harmonics of the 3rd, 5th, 7th, 11th and 13th orders culminating in a reduced true power factor of 0.944. Further computations and analysis on the network showed a reduction of the THD_I level from 16.43% to 8%. Modelling and simulation of the electrical distribution system was also carried out using Electrical Transient and Analysis Program (ETAP) software. The extracted harmonic waveforms and spectrums revealed harmonics of the 3rd, 5th, 7th and 9th orders to be more dominant within the network. Significant improvement of the true power factor with considerable savings of about Gh¢ 1,161,493.71 per annum was realised. The installation of tuned paralleled passive filters to mitigate harmonics gave a net present value of Gh¢ 2,736,028.00 at a discount rate of 8% with a payback period of 6.23 years.

Keywords: Harmonic Distortion, Non-Linear Loads, Distribution Network, Modelling and Simulation, Harmonic Mitigation, Harmonic Cost

1. Introduction

Electrical systems are extensively subjected to harmonic distortions in an unmitigated environment owing to the proliferation of non-linear loads that incorporate solid-state electronic components in their functionality and the increasing need for energy conservation. Arikan *et al.* suggests that the extensive usage of nonlinear loads is due to energy efficiency and improved functionality [1]. Consequently, cost of increased power losses and high utility bills are visible where the effects of harmonics are ignored. Other concession to the problem is noncompliance of equipment with harmonic standards, which further aggravates the pollution of the electrical network.

In Ghana, issues of power quality have not fully been addressed and harmonics in particular, with its attendant consequences has been totally ignored [2, 3]. Power system monitoring carried out by Electricity Company of Ghana (ECG) in 2012 showed that an estimated Gh¢ 2,400,000.00 per annum is lost as heat in the distribution network as a result of harmonics [2]. This is expected, as there is not a harmonic standard in place to establish checks and to regulate the influx of non-compliant imported electronic based equipment. The practical side of this unintentional negligence is the entailed costs such as increased leakage, transformer overload and derating, conductor overload, joules effect losses in lines and machinery, higher electrical consumption etc. that are not always easy to detect and evaluate [4, 5]. Therefore, it is important to take necessary steps to curb the increasing impacts of harmonics and realise some savings when quantified in absolute terms.

The electrical distribution network of the University of Cape Coast (UCC) accommodates over 80% nonlinear loads out of the total connected electrical loads. These harmonic producing loads create various disturbances on the electrical system. Meanwhile, newer installations with improved functionality and efficiency at the UCC do not conform to any harmonic standards. Overheating of electrical wirings in existing buildings is an outstanding issue in UCC owing to the high usage of electronics-based equipment. The existing building wirings were designed for relatively light office loads in the 1960s and 1970s, and may be overloaded by the present day trend of harmonic-producing loads [6, 7].

Magnetic or electronic ballast and capacitor banks including capacitors utilised in electrical equipment are prone to damages at the UCC. According to maintenance and procurement records, capacitors for motor starting and in air conditioners are indiscriminately botched. These capacitors and the auxiliary winding possibly create a series resonance that can be an ideal path for low-order harmonics which are already residing in the system thereby acting as harmonic sinks. Typical interaction of the capacitor motors with the system has no effect on power quality; however, damage to the capacitor motor due to excessive harmonic currents for which the motor generates a resonance condition may be of concern [8].

According to maintenance records obtained at the Electricity Section of the University, 55% of all lighting fluorescent tubes except for LEDs procured at the beginning of the year fuse out before end of year. Meanwhile, up to 35% of power packs become defective within the first three years according to the data obtained from the ICT Directorate of the University. 60% of the alternators in standby generators located at various facilities within the University have been rewinded at least once even though the operator defined limits for these generators in many cases were not exceeded.

Transformers situated at UCC hum quite nosily suggesting serious overloading and saturation. Conversely, various tests and measurements show a rather less loading with most units having around 65% although, increases in temperatures of hot spots and top oil was observed. This situation is akin to harmonic polluted power system according to Salles *et al.* and Zobaa *et al.* [9, 10].

Underground cables do not produce harmonics but the harmonic pollution at UCC is suspected to be exacerbated by the presence of underground cables which make up about 90% of the entire electrical distribution network according to the electrical distribution layout for the university. Cables may amplify any existing harmonic disturbances and can lower the frequency at which system resonance occurs due to the capacitance distributed along the cable length causing damage to capacitor banks [11].

The Electrical Installation Guide (2018) according to IEC International Standard suggests that, life span of equipment is significantly reduced when operated in harmonic environment exceeding 10% total harmonic distortion (THD). The estimated reductions are purportedly 32.5%, 18% and 5% for single-phase loads, three-phase loads and transformers respectively. This effectively means that to retain the service lives equivalent to a rated load, equipment must be oversized whereas existing equipment face the threat of hastened ageing and early deterioration, as is the case for UCC.

In terms of cost, the university spent an estimated total of Gh¢ 84 633.00 on replacement of 28 W electronic ballasts, 100 W LED floodlights, 250 W magnetic chokes for streetlights and 2.5 µF ceiling fan capacitors and 45 µF air conditioning capacitors for facilities other than residential on campus according to records on 2017 annual expenditure of electrical items obtained from the Central Stores. An average of 210 pcs of 23 W CFLs at a unit cost of Gh¢ 13.20 and 122 pcs of UPS at a unit cost of Gh¢ 750.00 were replaced in the year 2019 alone according to Maintenance of Existing Buildings (MEB) booklets obtained from the Electrical Maintenance Unit. 54 pcs of LED floodlights used for area security lighting succumbed and were replaced in the year 2018 at an estimated cost of Gh¢ 37 746.00. The ICT Centre alone replaced 47 pcs, 31 pcs and 43 pcs of PC power supply units (power packs) for 2017, 2018 and 2019 years respectively.

The principal objective of this paper therefore, is to ascertain the veracity of the harmonic distortions in the electrical systems on the university campus and evaluate the economic implications of the impact of harmonic disturbances.

2. Theoretical Framework

2.1. Economic Consequences of Harmonics

The circulation of harmonic currents within any system or installations presents a hidden liability. The economic implications of harmonic disturbances are difficult to evaluate and not easily noticeable. However, certain obvious effects exist in assessing the economic impact of harmonics.

The costs of harmonics are estimated in terms of equipment derating, premature aging of electrical equipment, misoperation of electrical systems and reduced power factor.

2.1.1. Equipment Derating

In a harmonic polluted environment, power sources such as transformers, generators and UPS systems are oversized. Neutral conductors are also oversized since circulating triplen harmonics in the system tend to add up in the neutral. The phase conductors owing to the excessive losses due to joule effect are also oversized. The cost associated with derating and overdesign can be weighty.

2.1.2. Premature Ageing of Electrical Equipment

Studies reveal that service life of equipment operated in harmonic environment exceeding 10% THD_I are set to reduce [12, 13]. The reduction, according to Electrical Installation Guide 2018 published by IEC International Standards has been estimated at 32.5% for single phase loads and 18% and 5% for three phase loads and transformers respectively thereby increasing their rate of replacement.

Table 1 shows the minimum service life expectancy for some selected harmonic loads [14].

Table 1. *Minimum Service Life Expectancy for some Selected Harmonic Loads.*

Harmonic Load	Expected Average Service Life
23 W CFLs	10 000 Lighting Hours
100 W LED Floodlights	50 000 Lighting Hours
28 W Electronic Ballasts	30 000 Lighting Hours
250 W HPS Magnetic Ballasts	65 000 Lighting Hours
2.5 μF Fan Capacitors (Class B)	10 000 Hours Run
45 μF A/C Capacitors (Class B)	50 000 Hours Run
PCs Power Pack	80 000 'ON' Hours
800 VA UPS Circuit Board	12 years

Frequent equipment replacement occasioned by harmonics can escalate capital expenses by 15% approximately and increase the costs of operation by virtually 10% [15].

2.1.3. Misoperation of Electrical Systems

The operating characteristics of frequency-dependent components within devices are affected by high harmonic frequencies which leads to misoperation of certain electronic component and the sporadic operation of circuit breakers which in turn results in nuisance tripping. This ultimately results in processes shutdown and operational downtimes. These downtimes can translate to huge financial losses.

2.1.4. Reduced Power Factor

The presence of harmonics increases the total apparent power demand in the network. Increase in the apparent power demand can plunge the contracted demand subscription into a higher tariff bracket. Also, depending on the tariff method employed by the utility, the reduction in the total power factor (PF) can result in power factor surcharges.

Typically, the PF are indicated on the utility bills as does ECG for bills submitted to customers. However, the indicated PF is the displacement power factor (DPF) and not the actual or true power factor. Owing to harmonics, distortion power factor (δPF) plays a crucial part in determining the true power factor (TPF) with significant savings potential [14, 16, 17].

Invariably, the presence of harmonics signifies a reduced true power factor where improvement unlike displacement power factor, is only possible by harmonics mitigation. When the THD_I is mitigated to 8% THD_I or lower, Grady and Gilleskie proved that the distortion power factor can be considerably improved thereby consequently improving the net true power factor [17].

2.2. Displacement Power Factor, Distortion Power Factor and True Power Factor

There arises a complication when the power factor is computed for a signal in a harmonic environment since the attendant frequencies of the harmonics superimposed on the fundamental signal is taken into consideration. Thus, the conventional definition of power factor as the cosine of the angle between fundamental frequency voltage and current has proceeded to consider the rms values of signals, which make up the contribution of components of different frequencies.

Displacement power factor (DPF) characterises the power frequency factor, while distortion power factors (δPF) emerges as the index that pursues rms signal disparities.

The distortion power factor is determined as:

$$\delta = \frac{1}{\sqrt{1+THD^2}} \quad (1)$$

The true power factor PF_{True} is defined as the product of the displacement power factor and distortion power factor. This is given by equation (2).

$$PF_{True} = DPF \times \delta PF = \cos\theta \times \frac{1}{\sqrt{1+THD^2}} \quad (2)$$

In essence, DPF pertains to fundamental quantities only and PF_{Tru} pertains to both fundamental and harmonic quantities. Where harmonics are not present, the two factors are indistinguishable. However, where harmonics are present, PF_{Tru} is always smaller than the DPF. In view of the fact that true power factor is always less than unity, it also holds that:

$$PF_{True} \leq DPF \quad (3)$$

2.3. Important Indicators for Testing Project Viability

2.3.1. Benefit-Cost Ratio

Benefit Cost Ratio (BCR) is the ratio of gross return and total cost. BCR is used in cost benefit analysis to ascertain the overall relationship between the relative costs and benefits of a proposed project. Sapkota S. and Sapkota S. expressed benefit cost ratio as a ratio of benefit to cost, thus a division of the proposed total cash benefits of a project by the proposed total cash outlays of the project [18]. If the proposed project has a BCR that is greater than 1.0, the project is expected to deliver a positive net present value and will generate an internal rate of return above the discount rate used in the discounted cash flow calculations and should therefore be accepted.

A BCR of exactly 1.0 indicates a break-even point where benefits of the proposed project equate the cost. If the BCR is less than 1.0, it means the project's costs outweigh the benefits and should not be considered [19].

2.3.2. Net Present Value

The Net Present Value (NPV) is one of two approaches engaged in deciding courses of action in capital budgeting when discounted cash flows are to be considered [20]. The method comprises the computation of the difference between the present values of a project's cash inflows and the present values of the expected cash outflows [21].

The NPV while simpler to use also makes some reasonable assumptions and these make it more credible than the Internal Rate of Return. The NPV uses the cost of capital as the discounting rate and screening tool. Projects with positive NPVs are deemed worthy of the required investment and provide insight into the economic efficiency and validity of the investment even though the criterion may not capture some practical considerations [22]. Projects with negative NPVs are rejected unless other factors dictate its acceptance [17].

3. Materials and Methods

3.1. The Power Distribution Network

The university is a Special Load Tariff (SLT) consumer and takes 11 kV bulk supply from the Electricity Company of Ghana (ECG) power network to its power distribution centre (PDC) located at the control station of the university. The 11 kV PDC equipped with a sulphur hexafluoride gas (SF_6) circuit breakers are fed from two 11 kV incoming feeders.

There are Sixteen (16) distribution transformer substations situated on the campus with a total installed capacity of 11.14 MW. Each substation is fitted with kVAr compensation equipment of appropriate capacity for power factor correction purposes. Table 2 shows the transformer substations and their respective nominal parameters. Underground cables of 3×185 mm^2 XLPE/PVC/SWA copper/aluminium are typically employed for the interconnection between the substations whereas armoured cables of 500 mm^2 single core XLPE/PVC/SWA copper are used for hooking the LV sides to the feeder pillars. In addition, these underground cables accounts for more than 80% of the high-tension (HT) distribution network. The HT distribution network on the campus has circuitry kilometres of 26.3 km.

3.2. Cost of Harmonics Due to Reduced Equipment Lifespan

Table 3 gives the estimated quantities of the selected harmonic loads replaced in 2017, 2018 and 2019 and total associated costs for academic and administrative facilities only. The selected harmonic loads at the university are evaluated in this thesis due to the rate of repairs and replacements performed on them. The harmonic loads include: 23 W CFLs, 100 W LED floodlights, 28 W electronic ballasts, 2.5 µF fan capacitors, 45 µF A/C capacitors, power supply units for computers and circuit boards for UPS.

Table 2. *Parameters of Transformer Substations Situated at the University of Cape Coast.*

Name of Substation	Transformer Capacity (kVA)	Impedance (%)	Full Load Current (A)	Secondary Line Voltage (V_{L-L})	Vector Group	Fitted Capacitor Bank (kVAr)
Auditorium	1000	4.54	1342	430	Dyn 11	245.0
Atlantic	1000	4.55	1342	430	Dyn 5	245.0
Science	1000	4.36	1332	433	Dy 11	245.0
Control Station	1000	5.61	1440	400	Dyn 5	200.0
CoDE	1000	4.47	1334	430	Dy 11	200.0
SRC/Medical	1000	4.56	1333	433	Dyn 11	245.0
Library	1000	4.56	1342	430	Dy 11	245.0
Northern	750	4.55	1008	433	Dyn 11	122.5
Casford	750	4.50	1000	433	Dy 11	125.5
Hill Top	630	4.54	840	433	Dy 11	125.5
Superannuation	500	4.05	696	415	Dyn 11	122.5
Ghana Hostels	500	4.41	667	433	Dyn 11	95.5
Southern	500	4.00	720	433	Dy 11	122.5
Valco-Trust	500	5.00	667	433	Dyn 11	95.5
Tech Village	100	4.28	135	430	Dy 11	46.0
Filling Station	50	5.65	69	433	Dyn 11	Nil

Table 3. *Annual Cost Estimation of Selected Harmonic Loads Replacement.*

Selected Harmonic Loads	Year of Replacement								
	2017			2018			2019		
	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)
CFLs	11.00	243	2673.00	12.50	176	2200.00	13.20	210	2772.00
100 W LED Lights	655.00	54	35370.00	699.00	54	37746.00	720	42	30240.00
28 W Electronic Ballasts	25.00	874	21850.00	26.50	652	17278.00	29.50	785	23157.50
250 W Choke	70.53	268	18902.00	77.25	200	15450.00	80.34	165	13256.10
2.5 µF Fan Capacitor	10.50	284	2982.00	12.10	165	1996.50	15.40	183	2818.20
45 µF A/C Capacitors	42.00	68	2856.00	48.00	71	3408.00	56.00	64	3584.00
PC PSUs	230.00	87	20010.00	246.00	52	12792.00	288.00	56	16128.00
800 VA UPS	505.00	175	189375.00	103.00	308	216524.00	287.00	150	91500.00
Total Associated Cost			193 018.00	166 795.00			183 455.80		

3.3. Measurement Points

Harmonic evaluations were carried out at the Point of Common Coupling (PCC) in compliance with harmonic limits as prescribed in the IEEE 519-2014 Standard. The point of common coupling according to the standard was taken as "the point in the electrical power system closest to the user, where other users are also connected.

For the commercial users supplied through a common service transformer, the PCC is the low voltage (LV) bus of the transformer whereas the high voltage (HV) side of the dedicated transformer is commonly the PCC for industrial users such as a production plant.

Figure 1 gives sample single line diagrams illustrating typical LV distribution arrangement of the Science Complex and University Hospital LV networks respectively. The PCCs at these typical facilities are identified.

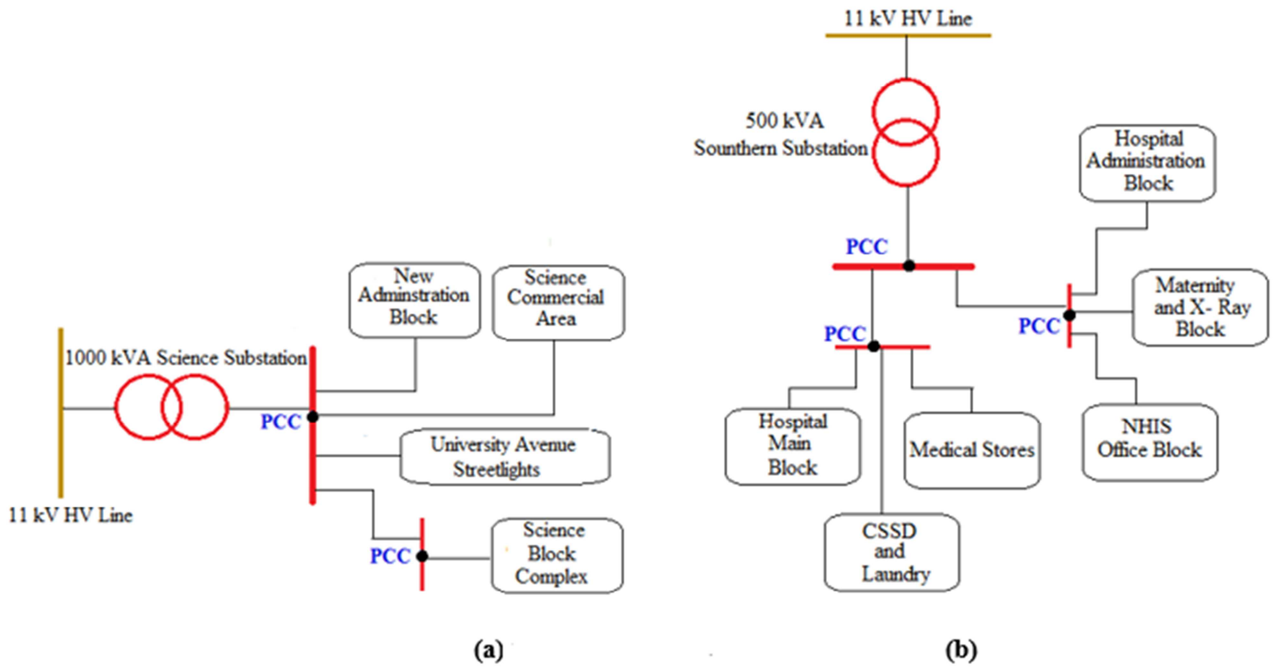


Figure 1. (a) Typical Distribution Arrangement showing the Location of PCCs at Science Complex LV Network, (b) Typical Distribution Arrangement showing the Location of PCCs at University Hospital LV Network.

3.4. Measurement Procedure

Chauvin Arnoux CA 8335 energy analyser qualistar+ was employed for the purposes of harmonic measurements for this paper owing to its shock resistant and rugged built including the ergonomics and simplicity of its interface which makes it simple and intuitive to use.

The analyser was installed with appropriate settings to capture measured data over a period of time as specified by IEEE 519-2014 standard. The duration for measurements as prescribed by the standard offers adequate period of time to sufficiently record and characterize the time varying nature of harmonic currents.

The transformers are strategically located close to the load centres on the university campus where the LV sides of the transformer are hooked directly onto the feeder pillars. The transformers and LV feeder pillars are housed separately in the same power house.

Choosing PCC involves identifying the PCC as specified by IEEE 519-2014 harmonic standard. Setting up is the process that deals with the correct way of installing the power analysing instrument at the PCC.

3.5. Determination of Short Circuit Ratio

Define The Short Circuit Ratio (SCR) at a particular location refers to the ratio of short-circuit current available, in amperes, to the load current, in amperes. The short circuit current I_{SC} is calculated using equation 4.

$$I_{SC} = \frac{kVA \times 100}{\sqrt{3} \times V_{L-L} \times \left(Z_{P.U} + Z_{System}\right)} \quad (4)$$

where kVA = transformer rating; V_{L-L} = line to line secondary voltage of the transformer at normal tapping; $Z_{P.U}$ = per unit impedance of the transformer at normal tapping; Z_{System} = estimated system impedances comprising service entrance equipment, cables and LV feeder pillars obtained from the UCC Electricity Section as 0.0155 per unit.

Equation 5 gives the relationship between the load current and short circuit current.

$$SCR = \frac{I_{SC}}{I_L} \quad (5)$$

where I_{sc} = short circuit current and I_L = maximum rated current obtained from the transformer nameplate.

The SRC values for each LV bus at the various PCCs were computed using the parameters given in Table 2 and equations 4 and 5. The summary SCR values for each substation are depicted in Table 4.

Since the SCR values are not up to 20, current distortion limits corresponding with values stated in the SCR < 20 category for which the maximum allowable THD_I values for daily 99th percentile is 8%, 4%, 3% and 1.5% for harmonic orders up to the 11th, 17th, 23rd, and 35th respectively was applied in this study. Similarly, voltages at the LV buses across the PCCs are less than 1.0 kV and therefore a recommended THD_V limit of 12% was used.

Table 4. *Summary of SCR Values for each Substation.*

Name of Substation	Transformer Capacity (kVA)	Per Unit Impedance	I_L (A)	I_{SC} (kA)	SCR
Auditorium	1000	0.0454	1342	22.05	16.43
Atlantic	1000	0.0455	1342	22.01	16.40
Science	1000	0.0436	1332	22.56	16.90
Control Station	1000	0.0561	1440	20.19	14.02
CoDE	1000	0.0447	1334	22.15	16.60
SRC/Medical	1000	0.0465	1333	21.51	16.14
Library	1000	0.0456	1342	21.98	16.37
Northern	750	0.0455	1008	16.40	16.42
Casford	750	0.0450	1000	16.53	16.53
Hilltop	630	0.0454	840	13.79	16.42
Superannuation	500	0.0405	696	12.42	17.74
Ghana Hostels	500	0.0441	667	11.19	16.78
Southern	500	0.0400	720	12.01	16.68
Valco-Trust	500	0.0500	667	10.18	15.26
Tech Village	100	0.0428	135	2.30	17.10
Filling Station	50	0.0565	69	1.18	17.20

3.6. Measurement Setup

Typical measurement setups at some of the substations and facilities of the university are illustrated in Figures 2 and 3.

(a) (b)

Figure 2. *(a) Measurement Setup at the Science Substation; (b) Measurement Setup at the Library Substation.*

(a) (b)

Figure 3. *(a) Measurement Setup at the Auditorium Substation; (b) Measurement Setup at the Control Station.*

3.7. Monitoring Duration

Harmonic measurements are performed over a period to characterize the variable nature of the harmonic levels. For very stable conditions such as those encountered in a commercial facility like hospitals, schools and universities, interdepartmental stores and shopping malls, banks and other businesses, measurements over single day are adequate to characterize the varying levels of harmonics.

However, for facilities such as steel plants with arc furnaces or manufacturing and production firms with varying production demands from clients, conducting a weeklong measurement is recommended [23]. Moreover, where operational characteristics vary from day to day, it is recommended to monitor over longer periods. Again, for a university environment, where the load types are similar throughout, the expected spectra content can easily be characterized in short term measurement.

The IEEE 519-2014 Standard recommends the measurement window widths such as: very short time harmonic measurements and short time harmonic measurements.

3.7.1. Very Short Time Harmonic Measurements

Very short time harmonic values are assessed over a 3-second interval based on an aggregation of 15 consecutive 12 (10) cycle windows for 60 (50) Hz power systems. Individual frequency components are aggregated based on rms calculation as shown in equation 6.

$$F_{n,vs} = \sqrt{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^2} \tag{6}$$

where F = voltage (V) or current (I), in rms value; n = harmonic order; i = simple counter; vs = "very short".

For very short time harmonic measurements, the duration is 24 hours (1 day) and the 99th percentile value (values should be less than 1.5 times and 2 times for voltages and currents respectively of the values recommended) should be calculated for each 24-hour period for comparison with the recommended limits in Clause 5 of the IEEE 519- 2014 Standard. This is applied to both voltage and current harmonics.

3.7.2. Short Time Harmonic Measurements

Short time harmonic values are assessed over a 10-minute interval based on an aggregation of 200 consecutive very short time values for a specific frequency component. The 200 values are aggregated based on rms calculation as shown in equation 7.

$$F_{n,sh} = \sqrt{\frac{1}{200}\sum_{i=1}^{200} F_{n,i}^2} \tag{7}$$

where F = voltage (V) or current (I), in rms value; n = harmonic order; i = simple counter; sh = "short".

The duration for short time harmonic measurement is a 7-day period (1 week); the 95th and 99th percentile values (i.e., for values exceeding 5% and 1% of the measurement period) should be calculated for each 7-day period for comparison with the recommended limits in Clause 5 of the IEEE 519-2014 Standard. These statistics should be used for both voltage and current harmonics with the exception that the 99th percentile short time value is not recommended for use with voltage harmonics [23].

In this paper, the "very short time" measurement duration was found optimal and was selected in view of time constraints, resources, similarity of electric loads and the large area to be considered for the measurement. Furthermore, the stable operating conditions prevailing on the distribution network of the university permits the adoption of the "very short time" measurement method.

3.8. Recommended Harmonic Limits

The IEEE 519-2014 prescribes the daily percentile values of each harmonic and THD at the PCC for voltage and current limits. Limits for line-to-neutral voltage harmonics in 415 V systems with daily 99th percentile very short time (3 s) harmonic currents are applied with respect to Table 5 [23].

Table 5. *Voltage Distortion Limits.*

Bus Voltage at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
V ≤ 1.0 kV	7.5	12

Limits for the current distortion by odd harmonics in 415 V systems daily 99th percentile very short time (3 s) harmonic currents are applied according to the ratio I_{SC}/I_L shown in Table 6 [23].

Table 6. *Current Distortion Limits.*

Maximum Harmonic Current Distortion in Percent of I_L					
Individual Harmonic Order (Odd Harmonics)					
I_{SC}/I_L	**3 ≤ h < 11**	**11 ≤ h < 17**	**17 ≤ h < 23**	**23 ≤ h < 35**	**TDD**
< 20	8.0	4.0	3.0	1.2	10.0
20 < 50	14.0	7.0	5.0	2.0	16.0
50 < 100	20.0	9.0	8.0	3.0	24.0
100 < 1000	24.0	11.0	10.0	4.0	30.0
>1000	30.0	14.0	12.0	5.0	40.0

3.9. Modelling and Simulation Software

Complexities arise from harmonics studies in relation to its propagation and interaction of voltage and current distortions where the impedance is shared including partial cancellation due to diversity of phase angles. Owing to this, it is necessary to model the affected network and conduct harmonic analysis to examine and identify possible violations of harmonic distortions limits including designing and testing filters for mitigation.

Several software are employed for power system analysis. In this paper, ETAP 16.0.0 was chosen to model the UCC distribution network and to conduct harmonic load flow studies.

4. Results and Discussions

4.1. Results

Two results are presented. Results obtained from a harmonic field study conducted at PCCs located at 16 substations including 5 special installations identified and results obtained from ETAP simulations of the modelled UCC distribution network.

4.1.1. Results of Harmonic Field Study at PCCs Located at the 16 Distribution Substations and at 5 Identified Special Installations

The field study results are presented in Table 7 and Table 8 for the main PCCs and special installation PCCs respectively. This captures the 99th percentile values of THD_V and THD_I as specified by the very short time measuring method prescribed by the IEEE 519-2014 Standard. The bolded values in Table 7 and Table 8 are those which did not violate the limits set by the harmonic standard.

Table 7. *Field Results on Three Phase System at Main PCCs.*

Location of Main PCCs	99th Percentile Values of Current and Voltage THD (%)					
	THD_I			THD_V		
	A1	A2	A3	V1	V2	V3
Auditorium	14.5	18.7	24.3	13.0	6.8	9.5
Atlantic	70.5	34.2	34.8	1.6	1.6	1.5
Science	9.8	7.7	11.2	1.9	2.4	1.5
Control Station	8.5	9.2	10.1	1.7	1.5	1.5
CoDE	10.4	7.9	12.0	2.3	2.2	2.4
SRC/Medical	11.2	11.2	10.0	1.5	1.6	1.6
Library	6.3	6.7	7.4	1.9	1.5	1.4
Northern	10.2	8.6	10.0	2.9	2.5	2.6
Casford	18.4	16.0	12.3	1.4	1.9	1.6
Hilltop	7.3	6.6	7.6	1.1	1.1	1.1
Superannuation	22.9	16.6	24.6	1.7	1.5	1.5
Ghana Hostels	21.9	24.4	68.4	1.8	2.1	1.7
Southern	17.9	31.3	23.6	2.7	2.2	2.6
Valco-Trust	9.8	9.6	6.9	1.5	1.6	1.4
Tech Village	8.0	7.2	8.5	2.4	1.6	1.7
UCC Filling St.	17.0	11.7	28.1	1.9	1.7	1.9

Table 8. *Field Results obtained from Special Installations PCCs.*

Location of Special Installation PCCs	99th Percentile Values of Current and Voltage THD (%)					
	THD_I			THD_V		
	A1	A2	A3	V1	V2	V3
Central Administration	26.8	261.9	82.9	18.6	52.8	85.3
University Hospital	17.0	14.4	20.7	2.4	1.6	1.7
University Press	39.2	28.4	25.9	2.5	2.0	2.2
ICT Centre	32.6	27.6	26.8	15.2	23.2	8.0
Streetlights	16.7	15.8	20.4	2.5	2.0	2.2

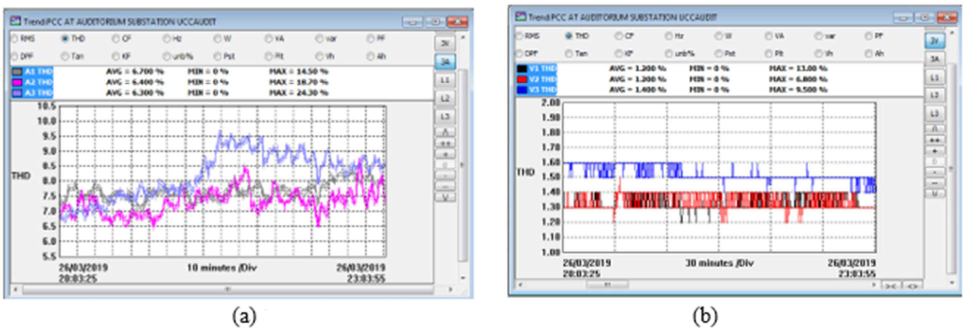


Figure 4. *(a) Waveforms of THD_I at the Auditorium PCC; (b) Waveforms of THD_V at the Auditorium PCC.*

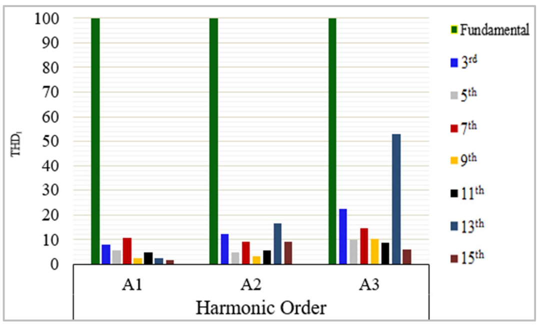


Figure 5. *THD_I Harmonic Spectrum for Auditorium PCC.*

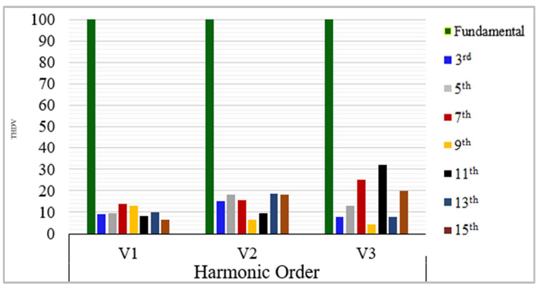


Figure 6. *THD_V Harmonic Spectrum for Auditorium PCC.*

Figure 4 shows the waveforms of THD_I and THD_V at the

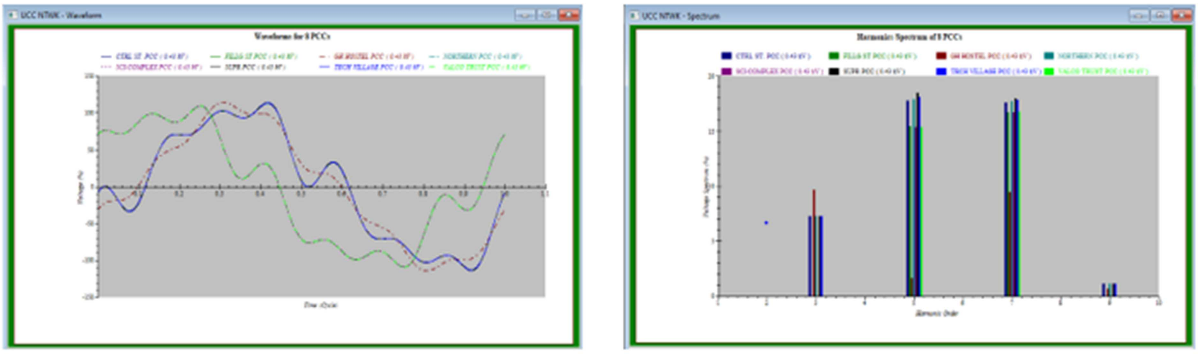
Auditorium PCC, while their corresponding harmonic spectra up to the 15th harmonic order are displayed in Figure 5 and Figure 6. The results for the remaining 15 substations in addition to 5 special installations were also analysed.

Table 9. *Averages of THD for Field Results on Three Phase System at Main PCCs.*

Location of Main PCCs	Average THD_I (%)	Average THD_V (%)
Auditorium	19.17	9.77
Atlantic	46.50	1.57
Science	9.57	1.93
Control Station	9.27	1.57
CoDE	10.10	2.30
SRC/Medical	10.80	1.57
Library	6.80	1.60
Northern	9.60	2.67
Casford	15.57	1.63
Hilltop	7.17	1.10
Superannuation	21.37	1.57
Ghana Hostels	38.23	1.87
Southern Substation	24.27	2.50
Valco-Trust	8.77	1.50
Tech Village	6.80	1.60
UCC Filling St.	18.93	1.83
Average THD	16.43	2.29

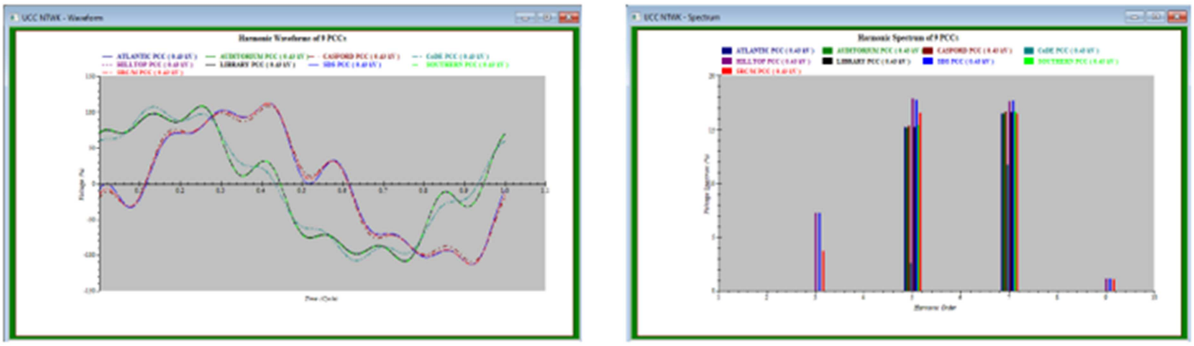
4.1.2. Results from Harmonic Analysis and Simulation Using ETAP Software

Harmonic waveforms and their respective spectrums of 8 LV buses and 9 LV buses with filters switched OFF and ON are depicted in Figure 7 to Figure 10.



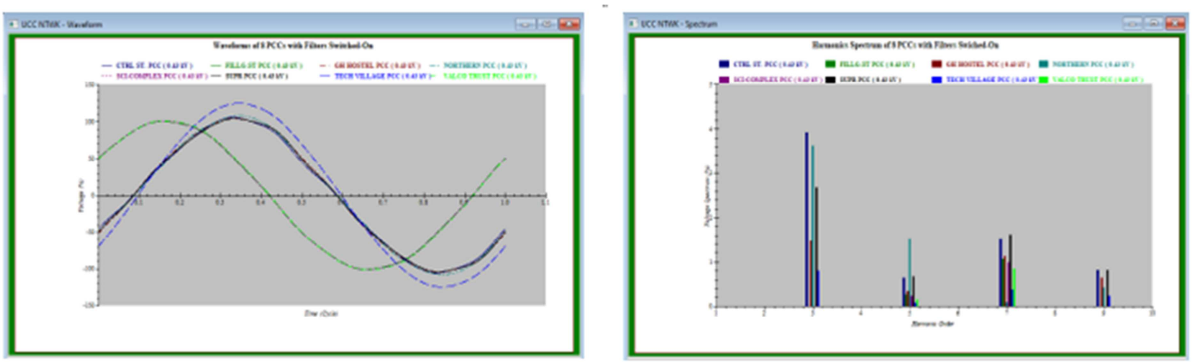
Waveform Harmonic Spectrum

Figure 7. *Waveform and corresponding Harmonic Spectrum of Eight (8) LV Buses with Filters Switched-OFF.*



Waveform Harmonic Spectrum

Figure 8. *Waveform and corresponding Harmonic Spectrum of Nine (9) LV Buses with Filters Switched-OFF.*



Waveform Harmonic Spectrum

Figure 9. *Waveform and corresponding Harmonic Spectrum of Eight (8) LV Buses with Filters Switched-ON.*

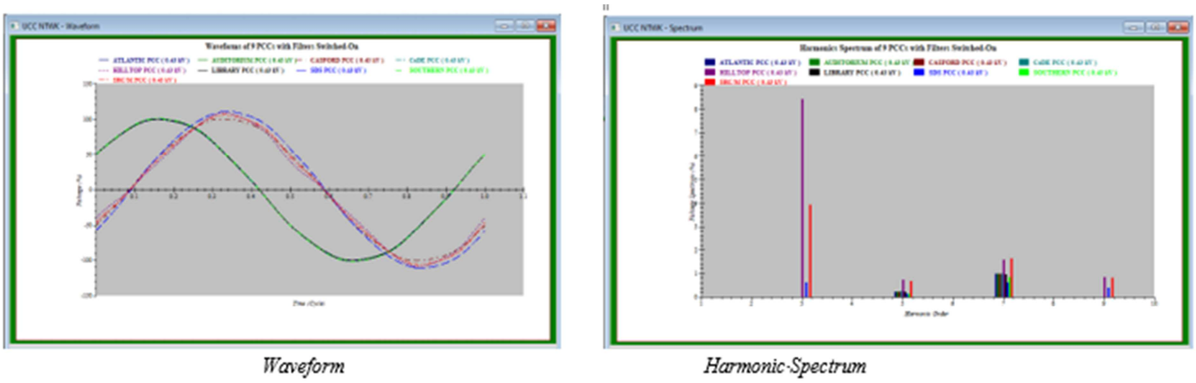


Figure 10. *Waveform and corresponding Harmonic Spectrum of Nine (9) LV Buses with Filters Switched-ON.*

4.1.3. Results on Cost Savings of Improved True Power Factor by Harmonics Mitigation

Power factors which are usually indicated on utility bills are not the actual or true power factors but rather displacement power factors. The distortion power factor obtained from the harmonic field measurement indicates an average of 0.944 across all PCCs as shown in Table 10. Table 11 shows a summary of 2017 SLT billing elements recorded for UCC energy consumption at an energy charge of Gh¢ 0.7809. However, the Contracted kVA Demand for UCC is 2109.5.

Table 10. *Field Results for Measured Power Factors at Main PCCs.*

Location of Main PCC	Displacement Power Factor (DPF)	Distortion Power Factor (δPF)	True Power Factor (TPF)
Auditorium	0.989	0.967	0.854
Atlantic	0.987	0.864	0.896
Science	0.992	0.908	0.927
Control Station	0.994	0.935	0.879
CoDE	0.996	0.884	0.985
SRC/Medical	0.998	0.989	0.981
Library	0.997	0.983	0.954
Casford	0.988	0.957	0.924
Hilltop	0.985	0.935	0.927
Northern	0.991	0.941	0.930
Superannuation	0.992	0.939	0.959
Ghana Hostels	0.988	0.943	0.932
Southern	0.989	0.967	0.956
Valco-Trust	0.985	0.941	0.927
Tech Village	0.993	0.965	0.958
Filling Station	0.979	0.958	0.938
Average Power Factors Measured at Main PCCs	0.991	0.944	0.935

Table 11. *Summary of Registered Power Components of Monthly Electricity SLT Bill for UCC in 2017.*

Month	Active Energy Consumed (kWh)	Apparent Energy Consumed (kVAh)	Maximum Demand (kVA)	Displacement PF (DPF)	Distortion PF (δPF)	True PF (TPF)
Jan	513887.87	529411.00	1779.11	0.971	0.955	0.927
Feb	680594.96	695640.00	2119.16	0.978	0.948	0.928
Mar	818970.91	830763.00	2083.00	0.986	0.942	0.929
Apr	763126.00	775512.00	2099.00	0.984	0.945	0.930
May	744062.57	755843.00	2010.73	0.984	0.946	0.931
Jun	545832.18	557596.00	1593.73	0.979	0.952	0.932
Jul	507789.66	519783.00	1291.90	0.977	0.955	0.933
Aug	458425.89	470685.00	1170.57	0.974	0.958	0.933
Sep	640079.41	651703.00	1632.91	0.982	0.951	0.934
Oct	796549.44	807790.00	1936.63	0.986	0.948	0.935
Nov	806671.03	816848.81	2016.99	0.988	0.948	0.936
Dec	686504.00	698015.00	1717.00	0.984	0.953	0.937

To reduce the THD_I from the recorded average of 16.43% to 8% (8% being the recommended limit for daily 99th percentile monitoring method for harmonics orders up to 11th harmonics), the distortion PF must be improved from an average of 0.9424 to 0.9968 in the distribution system. To achieve that, a multiplier K derived by substituting 8% into equation (1) yielded a value of 1.003195. Multiplying K by the displacement power factors in Table 11 yielded the improved values of new true power factor (New TPF) in Table 12 and the corresponding potential cost savings of Gh¢ 690 360.43 calculated in Table 13.

Table 12. *Calculated Consumption Elements of Monthly Electricity Bill for UCC in 2017.*

Month	Energy Charge @ 0.7809	Calculated Reactive Energy ($kVArh_1$)	New True Power Factor (New TPF)	Apparent Energy Consumed ($kVAh_2$)	Reactive Energy Consumed ($kVArh_2$)	$kVArh_{(diff)}$ ($kVArh_1$-$kVArh_2$)
Jan	401295.04	127260.61	0.974	500413.63	120053.52	7207.10
Feb	531476.60	143894.09	0.981	668002.78	132770.67	11123.43
Mar	639534.38	139476.92	0.989	809925.67	122738.29	16738.63
Apr	595925.09	138049.16	0.987	753337.07	123421.41	14627.75
May	581038.46	132926.79	0.988	734805.98	118475.13	14451.67
Jun	426240.35	113932.13	0.982	536023.69	104896.50	9035.63
Jul	396532.95	111013.64	0.980	497658.01	102984.72	8028.92
Aug	357984.78	106724.28	0.977	447912.60	99905.76	6818.53
Sept	499838.01	122536.32	0.985	630671.71	110969.19	11567.13
Oct	622025.46	134289.51	0.989	787974.86	117830.13	16459.39
Nov	629929.41	128545.08	0.991	799165.26	110817.45	17727.63
Dec	536090.97	126242.62	0.987	677340.04	113307.94	12934.68

Table 13. *Calculated Energy Savings from Monthly Electricity Bill for UCC in 2017.*

Month	New True Power Factor (New TPF)	kVArh(diff) Converted to kWh	Energy Charge @ 0.7809 (GH¢)
Jan	0.974	30849.91	24 090.69
Feb	0.981	57019.74	44 526.71
Mar	0.989	111688.43	87 217.49
Apr	0.987	90444.75	70 628.31
May	0.988	90761.20	70 875.42
Jun	0.982	47017.19	36 715.72
Jul	0.980	39588.42	30 914.59
Aug	0.977	31287.38	24 432.32
Sept	0.985	66720.17	52 101.78
Oct	0.989	111267.93	86 889.13
Nov	0.991	129044.31	100 770.70
Dec	0.987	78367.94	61 197.52
Annual Cost Savings for 2017			690 360.40

With similar iterations where 8% THD_I is assumed to be the average harmonic levels in the distribution system, the SLT bills for 2018 and 2019 yielded potential cost savings of Gh¢ 790 276.65 and Gh¢ 1 460 575.27 respectively as indicated in Table 14. The estimated average annual cost of harmonic disturbances amounted to Gh¢ 1 161 493.71.

Table 14. *Estimated Average Annual Cost of Harmonic Disturbances.*

Year	Estimated Annual Cost of Replacement of Selected Harmonic Loads (Gh¢)	Cost Savings of Harmonic Mitigation (Gh¢)	Estimated Total Cost of Harmonic Disturbances (Gh¢)
2017	193 018.00	690 360.40	883 378.40
2018	166 795.00	790 276.65	957 071.65
2019	183 455.80	1 460 575.27	1 644 031.07
Estimated Average Annual Cost of Harmonic Disturbances			1 161 493.71

4.2. Discussions

4.2.1. Harmonic Field Study

The field results obtained are weighted against the bus voltages of the PCCs and SCR values calculated for each LV bus at the PCCs to determine the respective voltage and current distortion limits prescribed in Table 5 and Table 6 by IEEE 519-2014 harmonic standard.

In accordance with current distortion limits of Table 6, field results for THD_I obtained for Auditorium substation in Figure 4 clearly are in violation of the prescribed limits. The 99^{th} percentile (maximum) values recorded exceeds 8%. Similarly, THD_V of voltage harmonics results for Auditorium substation depicted in Figure 4 marginally exceeded the recommended 12% limit stated in Table 5.

The results obtained from the monitoring at the sixteen (16) locations of main PCC substations including results for Special Installations are summarised in Table 7 and Table 8. The currents and voltages waveforms and the respective harmonic spectrums up to the 15^{th} order where significant values were recorded for only Auditorium substation are shown in Figure 4 to Figure 6. The waveforms and their corresponding harmonic spectrums for the remaining substations were also analysed and it was observed that the 3^{rd}, 5^{th}, 7^{th}, 9^{th}, 11^{th}, 13^{th} and 15^{th} harmonics were the dominant harmonic orders which recorded significant values. The other harmonic orders from the 17^{th} to the 50^{th} mostly recorded values of less significance. The calculated average current harmonics distortions on the UCC distribution network from Table 9 gave a value of 16.43%.

4.2.2. ETAP Simulation

The results from Figure 7 to Figure 10 show that the harmonics of the 3rd, 5th, 7th and 9th orders are dominant whereas the higher order harmonics from 11th to the 50th presented docile or no values. This is because of the typical harmonic components (nonlinear loads) modelling available in the ETAP software.

A single - tuned passive filter paralleled with other filters singly tuned to a different harmonic order was selected and connected to the PCCs to reduce the harmonics on the modelled network. Table 15 shows the levels of THD reduction achieved when filters were connected to the network.

Table 15. *Summary of Simulation Results with Filters Switched ON and OFF.*

LV Bus (PCC)	Simulated Results of THD		Filter Tuned Harmonic Order
	Filter OFF	Filter ON	
Auditorium	10.44	1.00	3rd
Atlantic	10.28	1.01	3rd
Science	10.06	0.99	5th
Control Station	13.88	4.25	3rd, 5th
CoDE	10.31	1.01	7th
SRC/Medical	14.92	4.20	3rd, 5th
Library	10.27	0.98	5th
Northern	15.81	3.77	3rd, 5th, 7th
Casford	9.82	0.99	3rd
Hilltop	13.50	8.54	5th, 7th
Superannuation	14.85	3.21	3rd, 5th
Ghana Hostels	13.27	1.91	3rd, 5th
Southern	9.80	0.84	5th
Valco-Trust	9.25	0.84	5th
Tech Village	10.47	0.74	5th, 7th
UCC Filling St.	9.46	1.09	5th
SDS	13.33	0.88	3rd, 5th

4.2.3. Estimated Cost of Proposed Harmonic Mitigation Equipment

Tuned paralleled passive filters are proposed based on their performance and effectiveness in reducing the resident harmonics as shown by the simulation results of Figure 9 and Figure 10 including other considerations such as lowest cost compared with other harmonics solutions, simplicity of design with fewer components and additional power factor correction. Typical parameters for simulation purposes were selected based on the maximum line currents and the overall kVAr ratings. Since the harmonics of concern are of lower frequency, a high Q factor of 50 at a rated voltage of 0.433 kV was selected with the typical tuning factors as indicated in Table 16 [24].

Table 16. *Parameters for Paralleled Single Tuned Passive Filters.*

Harmonic Order	Tuning Order	Parameters of Capacitor, C			Parameters of Inductor, L		
		kVAr	μF	V_C (kV)	X_L (Ω)	I_L (A)	I Max (A)
3rd	2.95	45.42	771.1	0.629	0.4744	155.1	200
5th	4.81	45.42	771.1	0.526	0.1784	138.7	180
7th	6.73	45.42	771.1	0.492	0.0911	133.8	180
9th	8.66	45.42	771.1	0.472	0.0551	127.3	150
11th	10.59	36.33	616.8	0.466	0.0481	103.8	150
13th	12.51	36.33	616.8	0.454	0.0334	95.69	100
15th	14.44	32.70	555.2	0.451	0.0275	85.78	80

The pricing obtained for the mitigation equipment is typical and based on available market price at the time of the research [15, 25]. Table 17 gives a summary of estimated costs of harmonic mitigation equipment.

Table 17. *Estimated Cost of Harmonic Mitigation Equipment.*

Location of PCC	Transformer Capacity (kVA)	Max THDI (%)	Max Load (A)	kVAr Required	Cost @ $ 120/kVAr
Auditorium	1000	24.30	1013	650	78000
Atlantic	1000	70.50	684	650	78000
Science	1000	11.20	1051	650	78000
Control Station	1000	10.10	208	650	78000
CoDE	1000	12.00	714	650	78000
SRC/Medical	1000	11.20	432	650	78000
Library	1000	7.40	812	650	78000
Northern	750	10.20	247	400	48000
Casford	750	18.40	171	400	48000
Hilltop	630	7.60	264	315	37800

Location of PCC	Transformer Capacity (kVA)	Max THDI (%)	Max Load (A)	kVAr Required	Cost @ $ 120/kVar
Superannuation	500	24.60	487	270	32400
Ghana Hostels	500	68.40	357	270	32400
Southern	500	31.30	482	270	32400
Valco-Trust	500	9.80	296	270	32400
Tech Village	100	7.40	72	80	9600
50	17.00	38	30	3600	50
Total Cost of Mitigation Equipment					822 600.00

The value of kVAr required was typically selected based on the maximum THD_I measured at the PCC under consideration and not on the reactive compensation requirement of the system. This is due to the fact that, a danger of overloading may exists when the need for compensation is low and the production of harmonics is dominant within the distribution system. The selection was also done with recourse to the application data of the filter to be applied and expected load current on a particular circuit branch.

4.2.4. Economic Evaluation of Harmonic Disturbances

Based on the assumption that the service life of single-phase loads operated in harmonic environment exceeding 10% THD_I are reduced by 32.5%, this paper therefore safely assumes that 32.5% of the replacements effected on the selected loads are occasioned by the adverse effects of harmonics disturbances in the university since the average total current harmonic distortion was found to be 16.43% as depicted in Table 9. The selected harmonic loads were expected on the average to be in service for the stated duration depicted in Table 1 before attaining obsolescence.

This implies that the university incurred Gh¢ 62 731.00 in 2017 as avoidable cost due to harmonics. Similar computation revealed that, Gh¢ 54 208.20 and Gh¢ 59 623.10 for 2018 and 2019 respectively were lost due to frequent replacement exacerbated by harmonics.

The cost evaluation of harmonic disturbances at the university is estimated at an annual average of Gh¢ 1 161 493.71 as indicated in Table 14. This comprises losses due to reduced service life of equipment and losses due to reduced true power factor of the UCC distribution network. A 25 years life expectancy is assumed for the harmonic mitigating equipment at a total cost of $ 822 600.00.

The total present values of benefits and cost stand at Gh¢ 7,122,377.98 and Gh¢ 4,386,349.98 respectively; giving a net present value (NPV) of Gh¢ 2,736,028.00. The net present value yielded a positive figure, suggesting that embarking on a harmonic mitigation venture is worthwhile if considered.

The rule of thumb is to assume a slightly higher figure than the stated inflation for a discount factor. Therefore, with inflation of 7.90% [26], a discount factor of 8% was reasonably selected and a discounted payback period (DPBP) based on the present value and payback value yielded 6.23 years. The benefits-costs ratio (BCR) was also deduced to be 1.62.

5. Conclusions

The increasing use of nonlinear loads has given rise to harmonics problems on electrical distribution systems. The proliferation of these harmonic loads on the electrical distribution systems has unquestionable economic consequences on the overall finances of the university. The rate of replacement of susceptible nonlinear loads has been more frequent in the presence of harmonics distortions including an overall reduction in the true power factor of the system. The veracity of the harmonic distortions in the electrical distribution system of the University of Cape Coast has been ascertained to be high. Additionally, the economic implications of this disturbance have also been evaluated. The following conclusions were drawn from the study:

i) The calculated average THD_I over the entire distribution network of 16.43% far exceeded the recommended limits set by the IEEE 519-2014 Standard. This is an indication of the extent of harmonic pollution in the distribution network of the university;
ii) The high THD_I resulted in an increase in the distortion power factor which is a component of the true power factor. This consequently led to a lowered overall true power factor; and
iii) A reduced true power factor for a special load tariff consumer such as the university, meant that large sums of money are lost. The analysis showed that, by mitigating the harmonics in the system to effect an overall reduction of the THD_I from an average of 16.43% to 8% leads to a significant savings of up to Gh¢ 1,161,493.71 per annum.

6. Recommendations

The following recommendations are made from the research conducted:

i) In view of the daunting outlay that must be expended in embarking upon harmonics mitigation, the university should consider as a matter of policy to gradually replace nonlinear loads with harmonics-compliant load types as a way of reducing the overall harmonics in the electrical distribution system;
ii) A reconfiguration of the distribution network which aims to separate shared buses of nonlinear loads and linear loads is necessary and should be considered with the nonlinear loads bus connected upstream of the network. This will minimise the overall impacts of harmonics at the main feeder bus and consequently reducing the levels of harmonics distortions; and
iii) The use of a tuned paralleled passive filter is recommended for harmonics mitigation as it is less expensive and proved effective in reducing the harmonic distortions to tolerable levels.

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