Analysis of High Neutral Currents and Harmonic Impacts on Losses and Capacities of Distribution Transformers

George Eduful, *Member, IAENG* and Kingsford J.A. Atanga

Abstract— **In this study, technical loss evaluation of distribution transformers in the Electricity Company of Ghana (ECG) distribution system is considered. The purpose is to estimate level and severity of losses in distribution transformers and show that system losses can significantly be reduced by reducing losses in distribution transformers. The focus is however on harmonic related losses. The study analyses harmonic contents of 148 distribution transformers of total capacity of 74 MVA. The number of transformers investigated represents 1.6% of the total number of distribution transformers in the ECG distribution system. The evaluation of the losses was based on ANSI/IEEE C57.110-1986. Impact of harmonics on capacities of the transformers was also examined. Results show that harmonic currents, especially zero sequence harmonics, can increase losses in distribution transformer to over 200%. The cost of energy per year resulting from the harmonic loss was found to be GHc 2,220,395.11/year (US$ 555,098.78/year). It was also found that the harmonic effect de-rates the total capacity of the transformers by 27%. In other words, to ensure that the transformers are working within their economic life span, their total capacity should be reduced by 20 MVA.**

Index Terms—**Harmonics, Triplen Harmonics, Distribution Transformers, Transformer Losses, Neutral Currents**

I. Introduction

SYSTEM losses in power distribution networks represent a major cost in the delivery of electric energy. Magnitude of the losses varies depending on the country and the state of the networks. Generally, system loss of around 6 to 8% is internationally accepted [1]. However, in developing countries, 20 to more than 40% system losses have been recorded [2, 3]. The problem is not different in Ghana: the president of the republic, in an address at function of the 2014 Ghana Journalists' Awards, put Ghana's system losses at 30% [4]. In the distribution system of the Electricity Company of Ghana (ECG), the losses are estimated at 23.54% (as at June, 2015) [5]. The problem of system losses continues to threaten the financial sustainability and operational efficiency of utility companies. As a result, effort to reduce losses in Ghana distribution system is a topmost priority. Accordingly, the ECG, in its budget for 2016, targets to reduce its system losses to less than 20% by end of 2016 [5].

System losses are made of commercial and technical losses. Whilst commercial losses relate to losses due to power theft and errors in billing systems, technical losses are inherent in the physical delivery of electric energy: it includes conductor and transformer losses. Therefore, to effectively deal with system losses, the effort should be focused on these two areas.

In this study, technical loss evaluation of distribution transformers in the ECG distribution system is considered. The purpose is to estimate level of losses in distribution transformers and show that system losses can significantly be reduced by reducing losses in distribution transformers. The focus is however on harmonic related losses and this is due to the presence of high neutral currents in most of the transformers.

High neutral currents in distribution transformers normally result from two situations. The first, and most common, is one where there are simply heavily unbalanced loads. This situation is usually easy to explain and remedy: loads need to be evenly distributed across the phases to reduce the neutral current. However, in harmonic environment the situation is different. Whilst positive and negative sequence components of harmonic current add to zero at neutral point, zero sequence harmonics do not. The zero sequence components are additive at the neutral and are the reason for high neutral current, even though the loads may be perfectly balanced [6]. Excessive neutral current usually results in high power losses in distribution transformers.

High neutral current can also generate potential difference between neutral and earth. The acceptable neutral to ground voltage is less than 0.5-3 V. However, neutral voltage of more than 7 V has been found [7]. High neutral voltage can cause system lockups, communication errors and operational problems [7].

The study analyses harmonic contents of 148 distribution transformers of mainly 500 kVA capacities. The evaluation of the harmonic losses was based on the IEEE Standard guidelines. Impact of harmonics on capacities of the distribution transformers was also assessed. Results show that harmonic currents, especially zero sequence harmonic currents, can increase losses in distribution transformers to over 200%. The cost of energy per year resulting from the harmonic loss was found to be GH¢ 2,220,395.11/year (US$

George Eduful is with the Electricity Company of Ghana, Accra, Box AN 5278, Accra-North, Ghana. Telephone Number : +233246132736; e-mail: eduful@ieee.org

Kingsford J. A. Atanga is with the Electricity Company of Ghana, Accra, Box AN 5278, Accra-North, Ghana. Telephone Number : +233249560723; e-mail: katanga23@gmail.com

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

555,098.78/year). Harmonic effect on the capacities of the transformers caused a total capacity loss of about 20 MVA.

II. HARMONIC THEORY

Harmonics are sinusoidal voltages and currents with frequencies that are integral multiples of the fundamental frequency that is 50 or 60 Hz in a typical power system. Mathematically, harmonic currents can be expressed as follows:

$$i_h = I_{DC} + \sum_h^n \sqrt{2} I_h \sin\left(2\pi f h + \delta_h\right) \quad (1)$$

where δ_h is the phase angle of the harmonic current and IDC is the direct component of the current (does not exist always). The equation of the harmonic voltages has the same form, but the current is replaced with voltage.

A. Harmonic Distortions and their Measurements

Total Harmonic Distortion (THD) is the most common index used to quantify harmonic distortion in power systems [8]. The THD value is the effective value of all the harmonics current or voltage added together, compared with the value of the fundamental voltage or current. Although many of today's test and measurement instruments can provide THD values, it is still important to understand the calculation that derives THD. The basic equation is as follows [9] :

$$THD_U = \frac{1}{U_1}\sqrt{\sum_{h=2}^{\infty} U_h^2} = \sqrt{\left(\frac{U_{rms}}{U_{1rms}}\right)^2 - 1} \quad (2)$$

where THD_U represents voltage or current total harmonic distortion (alternatively represented as THD_V and THD_I respectively) and *Urms* is the *rms* fundamental voltage or current.

Alternatively, rms voltage or current can be represented in terms of total harmonic distortion as given below.

$$U_{rms} = \sqrt{\sum_{h=1}^{\infty} U_{hrms}^2} = U_{1rms}\sqrt{1 + THD_U^2} \quad (3)$$

.

B. Effects of Harmonic Distortion

Harmonics have a number of undesirable effects on power system components and loads. The effects can be overheating of transformers, cables, motors, generators and capacitors connected to the same power supply with the devices generating the harmonics. Electronic displays and lighting may flicker, circuit breakers can trip, computers may fail and metering can give false readings [10]. According to [11] when the level of distortion in the supply voltage approaches 10%, the duration of the service life of equipment significantly reduces.

III. METHODOLOGY

One hundred and forty-eight (148) distribution transformers with high neutral currents were identified and purposively selected for the study. Capacities of the transformers ranged between 200 to 500 kVA at 11/0.433kV voltage level. Load on the transformers and harmonic contents were measured using the Megger Power Analyzer, model PA9 Plus. The measurement spanned for 12 hours at every distribution transformer station.

Load loss and winding resistance of the transformers were measured at a transformer workshop of the Electricity Company of Ghana. A Three Phase Precision Analyzer with model number VPA-60080, manufactured by Veer Electrical Instrument, was used for the load loss measurement. In the case of the winding resistance, the Megger instrument with the model number MT0210 was used. The measured values were all corrected to a reference temperature of 75 degree Celsius.

To determine the cause of the high neutral currents, the load distribution on the transformers and the respective harmonic contents were analysed. Based on the level of loading and the respective harmonic contents measured, power losses in the transformers were evaluated using the method prescribed in the ANSI/IEEE C57.110-1986. Total cost of energy arising from the power losses was then estimated for a period of 1 year. In the cost estimate of the energy loss, load factor of each transformer was considered. Fig 1 shows a sample of how the load factors were calculated.

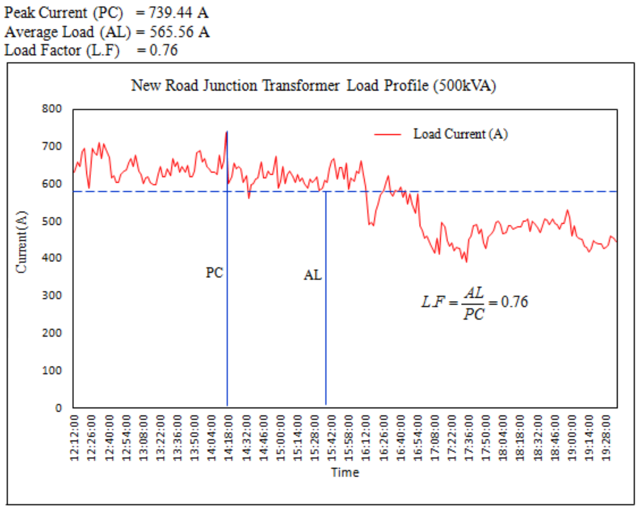


Fig 1: A sample of how load factors were determined

A. Analysis of High Neutral Current in Typical Distribution Transformers

In this section, harmonic and sinusoidal currents (fundamental) in a typical transformer neutral conductor are examined. Even though the focus of the study is on harmonic loss evaluation in distribution transformers, it is important to understand how fundamental and harmonic current contribute to high neutral current. The section also gives an overview of how unbalanced load can result in significant power losses.

Figure 2 shows a sample of a three phase load profile of a 500 kVA transformer. The current in the transformer neutral is also shown. Ordinarily, it would be thought that the current in the neutral represents the vector sum of the three phase loads. However, analysis of the neutral current showed that the current was composed of fundamental and

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

'triplen' harmonic currents, see Fig 3. Triplen harmonics are zero sequence harmonics that are in third multiples of the fundamental. It is important to note the variations in both the fundamental and the triplen harmonic content. Whereas the coefficient of variation of the fundamental is 43%, the variation in the triplen harmonics is 7.8%.

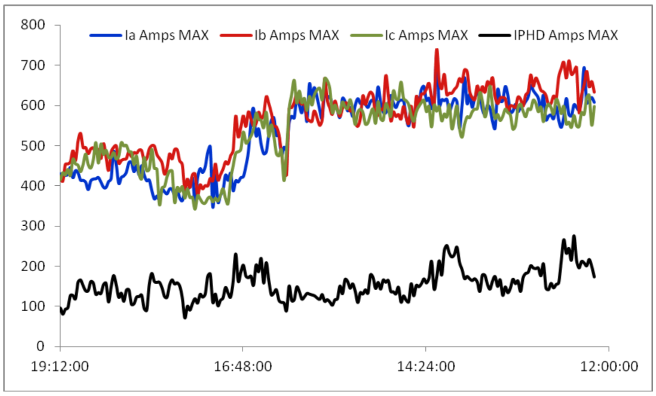


Fig 2: Three Phase Load Profile and Corresponding Neutral Current in a 500kVA transformer

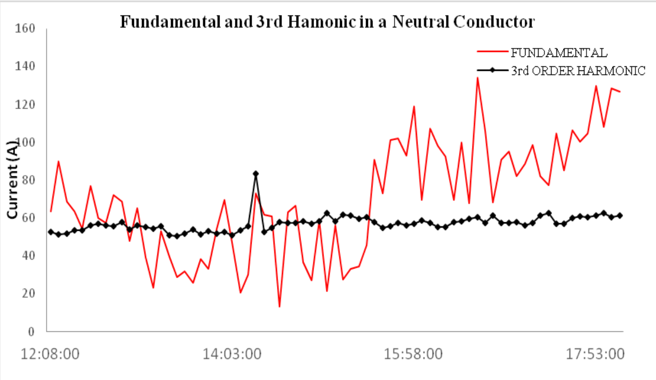


Fig 3: Fundamental and 3rd Harmonic Current in the Neutral Conductor

The high fundamental current and its large variations can be explained by unbalanced load and load variations or changes in the three phase supply. High fundamental current in the neutral is undesirable as it results in power losses. The most effective way of reducing fundamental current in the neutral is to ensure that the loads are almost balanced across the three phase supply. As an example, (4) and (5) can be used to illustrate power losses in distribution lines in balanced and unbalanced load conditions.

Balanced condition,

$$P_{line\_losses} = 3 \times R_f \times I_1^2 \tag{4}$$

Unbalanced condition,

$$P_{loss} = \left(I_1^2 + I_2^2 + I_3^2\right) \times R_f + I_N^2 \times R_N \tag{5}$$

where Rf is resistance per phase of a distribution line in Ω/km; I1, I2, I3 are the three phase currents drawn by the load; IN is the current in the neutral under unbalanced condition and RN is the resistance of the neutral conductor in Ω/km. Under balanced condition, I1=I2=I3.

As can be seen from (4) and (5), power losses under balance condition are limited only to the three phases of the distribution lines. However, under unbalanced condition, current in the neutral results in additional losses. The losses in the neutral can be very significant depending on the circuit length of the distribution system.

The low variation in the triplen harmonics, as shown in Fig 3, is explained by the fact that the triplen harmonics in the neutral conductor are not affected by balanced or unbalanced load conditions. The variation may be due to normal load changes experienced by distribution system. Presence of the triplen harmonics results in significant power losses and this is considered in the next section.

B. *Transformers Losses in Harmonic Environment*

Generally, transformers are manufactured such that minimum losses occur in rated voltage, rated frequency and sinusoidal current. However, in harmonic environment, the load current is no longer sinusoidal. The distorted load currents, resulting from harmonics, cause extra losses in transformers. According to [12, 13], transformer losses are categorized as no-load loss; load loss; and total loss. This is shown in (6) below.

$$P_T = P_{NL} + P_{LL} \tag{6}$$

where PT is the total loss, PNL is the No-load loss and PLL is the Load-loss.

No-load loss is due to the voltage excitation of the transformer core. In most power systems, the harmonic distortion of the system voltage THDv is well below 5% and the magnitudes of the voltage harmonics components are small compared with the fundamental component. Therefore, harmonic effects on no-load losses are often neglected. However, if THDv is not negligible, losses under distorted voltages can be calculated based on ANSI-C.27-1920 standard with (7)

$$P = P_M \left[P_h + P_{ec} \left(\frac{V_{hms}}{V_{rms}} \right)^2 \right] \tag{7}$$

Where Vhrms and Vrms are RMS values of distorted and sinusoidal voltages, PM and P are no-load losses under distorted and sinusoidal voltages, Ph and Pec are hysteresis and eddy current losses, respectively.

Load loss (PLL) is subdivided into PI2R (ohmic) loss resulting from load current and dc resistance of the windings in watts and total stray loss PTSL caused by electromagnetic flux in the windings, core, core clamps, magnetic shield, enclosure or tank walls. The total load loss can then be stated as

$$P_{LL} = P_{I^2R} + P_{TSL} \tag{8}$$

The total stray loss comprises winding eddy loss PEC in watts and other stray losses POSL in clamp, tanks etc in

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

watts, given as

$$P_{TSL} = P_{EC} + P_{OSL} \tag{9}$$

Substituting (9) into (8) gives

$$P_{LL} = P_{I^2R} + P_{EC} + P_{OSL} \tag{10}$$

Transformer rated PI2R losses can be calculated as follows

$$P_{I^2R-rated} = K\left(I_{1-rated}^2 R_1 + I_{2-rated}^2 R_2\right) \tag{11}$$

where K = 1 for single phase transformer; K=1.5 for three phase transformer; I1-rated is the rated transformer current at the primary side; I2-rated is the rated transformer current at secondary side. R1 and R2 are the winding resistance of the transformer at the primary and the secondary side respectively.

$$I_{1-rated} = \frac{P_{kVA}}{\sqrt{3} \times V_1} \tag{12}$$

$$I_{2-rated} = \frac{P_{kVA}}{\sqrt{3} \times V_2} \tag{13}$$

where PkVA is the rated power of the transformer; V1 and V2 are rated primary and secondary voltage of the transformer respectively.

According to IEEE C57.110, for oil immersed transformer, eddy current loss can be estimated using the following relation

$$P_{EC} = 0.33 \times P_{TSL} \tag{14}$$

In harmonic environment, the eddy current loss is increased by a factor FHL and other stray losses also increased by a factor FHL-STR. Accordingly, in the presence of harmonics, (10) can be modified and expressed as

$$P_{LL} = P_{I^2R} + F_{HL} \cdot P_{EC} + F_{HL-STR} \cdot P_{OSL} \tag{15}$$

where

$$F_{HL} = \frac{\sum_{h=1}^{h=h\max} \left(\frac{I_h}{I_1}\right) \cdot h^2}{\sum_{h-1}^{h=h\max} \left(\frac{I_h}{I_1}\right)^2} \tag{16}$$

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h\max} \left(\frac{I_h}{I_1}\right) \cdot h^{0.8}}{\sum_{h-1}^{h=h\max} \left(\frac{I_h}{I_1}\right)^2} \tag{17}$$

Where Ih is the harmonic current (A) at the hth harmonic order and I1 is the fundamental current (A).

C. *Transformer Capacity Evaluation in Harmonic Environment*

Overheating of transformers is one of the effects of harmonics. Accordingly to ensure that the transformer is working within its economic lifespan, the rated power of the transformer needs to be de-rated in harmonic environment. This means the maximum permissible current of transformer in harmonic load must be determined. The equation that applies to linear load conditions is:

$$P_{LL-R}(pu) = 1 + P_{EC-R}(pu) + P_{OSL-R}(pu) \tag{18}$$

Where, PLL-R is rated load losses in per unit (pu); PEC-R is rated eddy current loss in per unit (pu), P_{OSL-R} is rated other stray loss in per unit (pu).

Note that the base current is rated current and base loss is the I^2R loss at rated current in watts.

A general equation for calculating the transformer losses when supplying a harmonic load is given follows:

$$P_{LL-R}(pu) = I^2(pu) \times \left[1 + F_{HL} P_{EC-R}(pu) + F_{HL-STR} P_{OSL-R}(pu)\right] \tag{19}$$

Accordingly, from (19) the maximum permissible load current of transformer under harmonic condition can be determined from (20) below.

$$I_{\max}(pu) = \left(\frac{P_{LL-R}(pu)}{1 + \left[F_{HL} P_{EC-R}(pu)\right] + \left[F_{HL-STR} P_{OSL-R}(pu)\right]}\right)^{1/2} \tag{20}$$

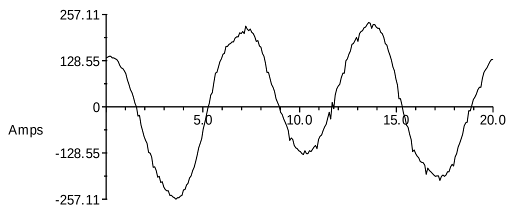
IV. Case Study in ECG Distribution System

As mentioned above, this case involved evaluation of harmonic losses in 148 distribution transformers. The capacities of the transformers in harmonic environment were also determined. In this section, results and discussions of the studies are presented.

Figure 4 below shows a sample of the harmonic load measurement obtained from the power disturbance analyzer. As can be seen in Fig 4, the THD of 314.31% is mainly due to the 3rd harmonic. Power losses resulting from these high harmonic contents were evaluated using (10) and (19).

Event: 7 Of 252	Event Triggered by Time
Duration: 1 Cycles	Event Trigger Cycle 1

Time:	01/01/2000 12:14:11.763
Input:	IPHD Amps
Cycle:	1



Cycle Waveform

Total Harmonic Distortion	314.31 %
Odd Contribution	313.76 %
Even Contribution	18.48 %
RMS Of Fundamental	44.29 A
RMS Of Fund + Harm	146.13 A
K Factor	9.18

Harm	% Of Fund	Amps	Angle	Harm	% Of Fund	Amps	Angle
Fund	100.00	44.3	0°	0	0.00	0.0	0°
3	313.18	138.7	38°	2	17.38	7.7	14°
5	7.40	3.3	134°	4	2.99	1.3	141°
7	11.01	4.9	143°	6	2.18	1.0	294°
9	10.94	4.8	160°	8	1.07	0.5	139°
11	5.37	2.4	149°	10	1.22	0.5	344°
13	3.55	1.6	82°	12	1.21	0.5	82°
15	0.26	0.1	338°	14	1.40	0.6	151°
17	1.36	0.6	204°	16	0.74	0.3	45°
19	1.75	0.8	48°	18	0.42	0.2	286°
21	0.82	0.4	47°	20	0.48	0.2	310°
23	0.90	0.4	155°	22	0.59	0.3	331°
25	0.46	0.2	270°	24	0.44	0.2	294°
27	0.80	0.4	122°	26	1.35	0.6	222°
29	2.43	1.1	181°	28	1.67	0.7	337°
31	0.99	0.4	41°	30	1.06	0.5	9°
33	0.54	0.2	238°	32	0.72	0.3	353°
35	1.38	0.6	253°	34	0.82	0.4	312°
37	0.86	0.4	136°	36	0.66	0.3	258°
39	0.70	0.3	281°	38	0.31	0.1	285°
41	0.26	0.1	262°	40	0.32	0.1	334°
43	0.54	0.2	63°	42	1.21	0.5	278°
45	0.71	0.3	307°	44	0.44	0.2	77°
47	0.62	0.3	136°	46	0.58	0.3	246°
49	0.41	0.2	206°	48	1.46	0.6	44°
51	1.08	0.5	16°	50	0.50	0.2	116°
53	0.93	0.4	205°	52	0.67	0.3	57°
55	0.57	0.3	294°	54	0.62	0.3	173°
57	2.42	1.1	276°	56	1.98	0.9	81°
59	0.59	0.3	219°	58	1.11	0.5	111°
61	0.69	0.3	83°	60	0.34	0.2	101°
63	0.43	0.2	237°	62	0.39	0.2	92°

Fig 4: A sample of the harmonic measurement

Table 1- Losses Estimation at Full Load Rating of the Transformers

ITEM No.	TRAFO NAME	TRAFO RATING	P_{LL-R}	I_{1-R}	I_{2-R}	R_1	R_2	P_{I^2R-R}	P_{TSL-R}	P_{EC-R}	P_{OSL-R}
1	4BN	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
2	ASAWASI RAILWAY QTRS	800	8000	42	1074	2.249	0.000858	4182	3818	1260	2558
3	A111	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
4	ADUM CENTRAL No.2	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
5	ADIEBEBA 7 DAYS	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
6	ADUM CENTRAL No.1	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
7	ADUM GUGGISBURG	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
8	ADUM STORAGE	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
9	DABAN (SPOKEN WORD)	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
10	J.E. NSIAH	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
11	KAASE TOTAL	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
12	KSTS	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
13	OWASS	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
14	SANTASI ZONGO No.2	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
15	ADIEMBRA F. G. C.	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
16	AGRIC NZIMA No.1	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
17	ALHAJI SALIA No.2	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
18	ATASOMANSO OLD T.	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
19	DANYAME DIST. OFF. 1	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
20	NHYIAESO D'DJOM (A124)	500	4268	26	671	2.256	0.0003122	1430	2838	937	1902
DETAILS FOR TRANSFORMER NOS. 21 TO 148 HAS BEEN TRUNCATED DUE TO SPACE CONSTRAINTS (AVAILABLE ON REQUEST)											
			P_{LL-R}					P_{I^2R-R}	P_{TSL-R}	P_{EC-R}	P_{OSL-R}
Total			**623,693**					**206,040**	**137,826**	**137,826**	**279,828**

For ease of computations, Microsoft Exel formatted with the above formulae were used, refer to Table 1.

From Table 1, the total load loss (PLL) at full load rating of the transformers without harmonic effect is

PLL= 623,693 Watts.

Based on the rated load losses of the transformers, the average load losses of the transformers at estimated average load on the transformers were determined. The results of the average load losses are shown in Table 2.

From Table 2, the total average load loss (PLL-A) of the transformers without harmonic effect is

PLL-A =515, 674 Watts

In harmonic environment, (15) applies. Accordingly, from Table 3, total load loss (PLL+H) of the transformers in presence of the harmonics is

PLL+H = 1,019, 806

Comparing PLL-A and PLL-H, it can be seen that operating transformers in harmonic environment can increase the load losses to about 200%.

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Table 2 - Losses calculation at Estimated Average Load on the Transformers without Harmonics

ITEM No.	TRAFO NAME	TRAFO RATING	I_1@A	I_2@A	R_1	R_2	P_{I^2R-A}	P_{TSL-A}	P_{EC-A}	P_{OSL-A}	P_{LL-A}
1	4BN	500	23	585	2.256	0.0003122	1469	2475	817	1658	3944
2	ASAWASI RAILWAY QTRS	800	36	928	2.2494	0.000858	4142	3299	1089	2210	7441
3	A111	500	21	543	2.256	0.0003122	1086	2295	757	1538	3381
4	ADUM CENTRAL No.2	500	16	417	2.256	0.0003122	379	1764	582	1182	2143
5	ADIEBEBA 7 DAYS	500	16	418	2.256	0.0003122	382	1767	583	1184	2149
6	ADUM CENTRAL No.1	500	11	290	2.256	0.0003122	88	1226	405	821	1314
7	ADUM GUGGISBURG	500	19	488	2.256	0.0003122	710	2063	681	1382	2773
8	ADUM STORAGE	500	18	459	2.256	0.0003122	557	1942	641	1301	2498
9	DABAN (SPOKEN WORD)	500	18	462	2.256	0.0003122	568	1951	644	1307	2519
10	J.E. NSIAH	500	23	586	2.256	0.0003122	1476	2478	818	1660	3953
11	KAASE TOTAL	500	18	450	2.256	0.0003122	511	1901	627	1273	2412
12	KSTS	500	22	559	2.256	0.0003122	1219	2362	779	1582	3580
13	OWASS	500	21	543	2.256	0.0003122	1089	2296	758	1538	3385
14	SANTASI ZONGO No.2	500	24	604	2.256	0.0003122	1663	2553	842	1710	4216
15	ADIEMBRA F.G.C	500	22	560	2.256	0.0003122	1231	2368	781	1586	3599
16	AGRIC NZIMA No.1	500	20	523	2.256	0.0003122	937	2212	730	1482	3149
17	ALHAJI SALIA No.2	500	21	548	2.256	0.0003122	1125	2315	764	1551	3440
18	ATASOMANSO OLD T	500	21	548	2.256	0.0003122	1125	2315	764	1551	3440
19	DANYAME DIST OFF 1	500	24	602	2.256	0.0003122	1648	2547	841	1706	4195
20	NHYIAESO D'DJOM (A124)	500	20	509	2.256	0.0003122	840	2152	710	1442	2991
DETAILS FOR TRANSFORMER NOS. 21 TO 148 HAS BEEN TRUNCATED DUE TO SPACE CONSTRAINTS (AVAILABLE ON REQUEST)											
							P_{I^2R-A}	P_{TSL-A}	P_{EC-A}	P_{OSL-A}	P_{LL-A}
TOTAL							**174060**	**341614**	**112733**	**228881**	**515674**

Table 3 : Losses Calculation at Estimated Average Load on the Transformer in the Presence of Harmonics

ITEM No.	TRAFO NAME	TRAFO RATING	I_1@A	I_2@A	P_{EC-A}	P_{OSL-A}	F_{HL}*P_{EC-A}	F_{HL-STR}* P_{OSL-A}	P_{I^2R-A}	P_{LL+H}
1	4BN	500	23	585	817	1658	2034	3918	1469	7422
2	ASAWASI RAILWAY QTRS	800	36	928	1089	2210	5897	5209	4142	15248
3	A111	500	21	543	757	1538	1064	3047	1086	5197
4	ADUM CENTRAL No.2	500	16	417	582	1182	2721	2691	379	5791
5	ADIEBEBA 7 DAYS	500	16	418	583	1184	1100	2461	382	3942
6	ADUM CENTRAL No.1	500	11	290	405	821	3592	1117	88	4797
7	ADUM GUGGISBURG	500	19	488	681	1382	3423	3439	710	7572
8	ADUM STORAGE	500	18	459	641	1301	887	2458	557	3902
9	DABAN (SPOKEN WORD)	500	18	462	644	1307	715	1970	568	3253
10	J.E. NSIAH	500	23	586	818	1660	3657	3973	1476	9105
11	KAASE TOTAL	500	18	450	627	1273	701	2314	511	3527
12	KSTS	500	22	559	779	1582	1781	3296	1219	6296
13	OWASS	500	21	543	758	1538	1064	2763	1089	4916
14	SANTASI ZONGO No.2	500	24	604	842	1710	4870	3529	1663	10063
15	ADIEMBRA F.G.C	500	22	560	781	1586	1224	3222	1231	5677
16	AGRIC NZIMA No.1	500	20	523	730	1482	2215	3475	937	6628
17	ALHAJI SALIA No.2	500	21	548	764	1551	1044	3070	1125	5238
18	ATASOMANSO OLD T	500	21	548	764	1551	2520	3552	1125	7197
19	DANYAME DIST. OFF. 1	500	24	602	841	1706	1353	3259	1648	6260
20	NHYIAESO D'DJOM (A124)	500	20	509	710	1442	1143	3220	840	5203
DETAILS FOR TRANSFORMER NOS. 21 TO 148 HAS BEEN TRUNCATED DUE TO SPACE CONSTRAINTS (AVAILABLE ON REQUEST)										
					P_{EC-A}	P_{OSL-A}	F_{HL}*P_{EC-A}	F_{HL-STR}* P_{OSL-A}	P_{I^2R-A}	P_{LL+H}
TOTAL					**112,733**	**227,223**	**349,835.05**	**497380**	**172591**	**1,019,806**

A. *Cost of Harmonic Energy Loss*

The cost of energy resulting from the total harmonic power losses can be calculated as follows [14]:

$$\sum\left[\left(P_{LL+H}-P_{LL-A}\right)\times LLF\right]\times 8760\times B$$

Where,

LLF= loss of load factor; B=Cost of energy in Ghana Cedis (GH¢ 0.67/kWh) and 24x365=8760 hrs in a year

Loss of Load Factor for urban systems [14]:

=

$$0.3\times\left(Load\_Factor\right)+0.7\times\left(Load\_Factor\right)^2$$

From a simple spreadsheet (see Table 4) calculation based on the above formulae, the annual cost of energy resulting from the harmonic power losses is

GHc 2,220,395.11/year (US$ 555,098.78/year)

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Table 4 : Estimation of Cost of Energy

ITEM NO.	TRANSFORMER NAME	kVA RATING	LOAD FACTOR (LF)	LOSS OF LOAD FACTOR (LLF)	P_{LL-A}	P_{LL+H}	$(P_{LL+H}-P_{LL-A})$ (kW)	NO. OF HOURS IN A YEAR	TOTAL COST OF ENERGY/YEAR
1	4BN	500	0.87	0.79	3944	7422	3.477	8760	16298
2	ASAWASI RAILWAY QTRS	800	0.86	0.78	7441	15248	7.807	8760	36032
3	A111	500	0.81	0.70	3381	5197	1.816	8760	7507
4	ADUM CENTRAL No.2	500	0.62	0.46	2143	5791	3.649	8760	9839
5	ADIEBEBA 7 DAYS	500	0.62	0.46	2149	3942	1.794	8760	4851
6	ADUM CENTRAL No.1	500	0.43	0.26	1314	4797	3.483	8760	5350
7	ADUM GUGGISBURG	500	0.73	0.59	2773	7572	4.799	8760	16662
8	ADUM STORAGE	500	0.68	0.53	2498	3902	1.404	8760	4417
9	DABAN (SPOKEN WORD)	500	0.69	0.54	2519	3253	0.734	8760	2327
10	J.E. NSIAH	500	0.87	0.80	3953	9105	5.152	8760	24190
11	KAASE TOTAL	500	0.67	0.51	2412	3527	1.115	8760	3389
12	KSTS	500	0.83	0.73	3580	6296	2.716	8760	11774
13	OWASS	500	0.81	0.70	3385	4916	1.531	8760	6335
14	SANTASI ZONGO No.2	500	0.90	0.84	4216	10063	5.847	8760	28863
15	ADIEMBRA F.G.C	500	0.83	0.74	3599	5677	2.078	8760	9047
16	AGRIC NZIMA No.1	500	0.78	0.66	3149	6628	3.479	8760	13532
17	ALHAJI SALIA No.2	500	0.82	0.71	3440	5238	1.798	8760	7542
18	ATASOMANSO OLD TOWN	500	0.82	0.71	3440	7197	3.756	8760	15757
19	DANYAME DIST. OFF 1	500	0.90	0.83	4195	6260	2.065	8760	10154
20	NHYIAESO D'DJOM (A124)	500	0.76	0.63	2991	5203	2.211	8760	8223
DETAILS FOR TRANSFORMER NOS. 21 TO 148 HAS BEEN TRUNCATED DUE TO SPACE CONSTRAINTS (AVAILABLE ON REQUEST)									
TOTAL							$(P_{LL+H}-P_{LL-A})$ (kW)	Hours in a Year	Cost of Energy/year (GHC)
							512	8760	2,220,395.11

Table 5: Estimation of Capacity Loss due to Harmonics

ITEM No.	TRAFO NAME	TRAFO RATING	$P_{I}^{2}{}_{R-}$	P_{EC-R}	P_{OSL-R}	$P_{EC-R(PU)}$	$P_{OSL-R(pu)}$	$F_{HL}*P_{EC-R(pu)}$	$F_{HL-STR}*P_{OSL-R(pu)}$	P_{LL-R}	I_{max}	ALLOWABLE CAPACITY DUE TO HARMONICS	CAPACITY LOSS DUE TO HARMONICS
1	4BN	500	1430	937	1902	0.655	1.330	1.631	3.143	2.985	0.719	359	141
2	ASAWASI RAILWAY QTRS	800	4182	1260	2558	0.301	0.612	1.632	1.442	1.913	0.685	548	252
3	A111	500	1430	937	1902	0.655	1.330	0.920	2.635	2.985	0.809	405	95
4	ADUM CENTRAL No.2	500	1430	937	1902	0.655	1.330	3.063	3.029	2.985	0.649	324	176
5	ADIEBEBA 7 DAYS	500	1430	937	1902	0.655	1.330	1.236	2.765	2.985	0.773	386	114
6	ADUM CENTRAL No.1	500	1430	937	1902	0.655	1.330	5.816	1.809	2.985	0.588	294	206
7	ADUM GUGGISBURG	500	1430	937	1902	0.655	1.330	3.293	3.309	2.985	0.627	313	187
8	ADUM STORAGE	500	1430	937	1902	0.655	1.330	0.907	2.514	2.985	0.822	411	89
9	DABAN (SPOKEN WORD)	500	1430	937	1902	0.655	1.330	0.727	2.004	2.985	0.894	447	53
10	J.E. NSIAH	500	1430	937	1902	0.655	1.330	2.930	3.183	2.985	0.648	324	176
11	KAASE TOTAL	500	1430	937	1902	0.655	1.330	0.732	2.417	2.985	0.848	424	76
12	KSTS	500	1430	937	1902	0.655	1.330	1.497	2.770	2.985	0.753	376	124
13	OWASS	500	1430	937	1902	0.655	1.330	0.920	2.389	2.985	0.832	416	84
14	SANTASI ZONGO No.2	500	1430	937	1902	0.655	1.330	3.787	2.744	2.985	0.630	315	185
15	ADIEMBRA F.G.C	500	1430	937	1902	0.655	1.330	1.026	2.701	2.985	0.795	397	103
16	AGRIC NZIMA No.1	500	1430	937	1902	0.655	1.330	1.988	3.119	2.985	0.699	350	150
17	ALHAJI SALIA No.2	500	1430	937	1902	0.655	1.330	0.895	2.632	2.985	0.812	406	94
18	ATASOMANSO OLD TOWN	500	1430	937	1902	0.655	1.330	2.161	3.045	2.985	0.694	347	153
19	DANYAME DIST OFF 1	500	1430	937	1902	0.655	1.330	1.054	2.540	2.985	0.806	403	97
20	NHYIAESO D'DJOM (A124)	500	1430	937	1902	0.655	1.330	1.055	2.971	2.985	0.771	385	115
DETAILS FOR TRANSFORMER NOS. 21 TO 148 HAS BEEN TRUNCATED DUE TO SPACE CONSTRAINTS (AVAILABLE ON REQUEST)													
TOTAL CAPACITY LOSS DUE TO HARMONICS													18909

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

B. Harmonic Effect on Capacities of the Transformers

The maximum allowable currents, in per unit, for decreasing the rated capacities of the transformers due to harmonic effects were determined. The de-rated values of the capacities are shown in Table 4. The overall capacity loss of the transformers is also shown in Table 4. As can be seen, the total capacity loss of the transformers is approximately 20 MVA.

It is important to note that this loss relates only to the 148 distribution transformers, representing 1.6% of total number of distribution transformers in ECG distribution network. Considering the current power crisis in the country, losing 20 MVA capacity to harmonics can be very disturbing, especially when solutions to harmonic problems can be very simple and inexpensive.

V. Conclusions

The study has analysed the contents of high neutral currents and investigated the main effects of harmonics on distribution transformers. The study therefore, concludes as follows:

1. Triplen Harmonics are most often responsible for high neutral currents in distribution transformers. They represent more than 70% of the RMS current in the neutral conductor.

2. Variation of the fundamental current in the neutral conductor is larger compared with variation of the triplen harmonic current. This variation is mainly due to unbalanced load conditions and frequent load changes in the three phase supply.

3. Whereas the fundamental current can be reduced by load balancing across three phase supply, the triplen harmonics cannot. To reduce the triplen harmonic currents, harmonic suppressing devices are required.

4. Harmonics can increase losses in distribution transformer to more than 200%. This represents a major cost in the delivery of electric energy. The study has shown that a total cost of energy of GHc 2,220,395.11/year (US$ 555,098.78/year) can be wasted through harmonic effects.

5. Harmonic effect de-rates capacity of transformers. In the study, harmonic effect reduced the total capacity of the transformers by 27%. In other words, the total capacity of the transformers had to be reduced by 20 MVA to ensure the transformers are working within their economic life span.

References

[1]. Raúl Jiménez, Tomás Serebrisky and Jorge Mercado, 2014: Sizing Electricity Losses in Transmission and Distribution Systems in Latin America and the Caribbean. Published by Inter-American Development Bank.

[2]. Ghana Sustainable Energy for All Action Plan, 2012. Online source, date access: 27th September, 2015. Available at energycom.gov.gh/files/SE4ALL-GHANA%20ACTION%20PLAN.pdf

[3]. Reducing Technical and Non-Technical Losses in the Power Sector, 2009. Background Study for the World Bank Group Energy Sector Strategy July 2009

[4]. ECG must check 'waste' in the system. Online source, date access: 27th August, 2015. Available at www.ghheadlines.com › CitiFm › 17th Aug, 2015.

[5]. The Managing Director of the Electricity Company of Ghana Planning letter for 2015 Budget.

[6]. M. Davudi, S. Torabzad, B. Ojaghi, 2011: Analysis of Harmonics and Harmonic Mitigation Methods in Distribution Systems. Australian Journal of Basic and Applied Sciences, 5(11): 996-1005, 2011. ISSN 1991-8178

[7]. Nandita Dey and A.K.Chakraborty, 2013: Neutral Current and Neutral Voltage in a Three Phase Four Wire Distribution System of a Technical Institution. *International Journal of Computer Applications (0975 – 8887) Volume 72– No.3, May 2013*

[8]. Browne, T.J. (2006). "Experience in the Application of IEC/TR 61000-3-6 to Harmonic Allocation in Transmission System". *41st International Conference on Large Voltage Electric Power System.* Paris, CIGRE 21.

[9]. Chaudhari, P. (2014). "Novel ways for Power System Harmonic Mitigation for Tidal power plant". Online source, date accessed: 12th February, 2013. Avalaible at *ijsae.in/ijsaeems/index.php/ijsae/article/view/97*

[10]. Mueller, A. (2011). "Switching Phenomena in Medium Voltage Systems - Good Engineering Practice on the Application of Vacuum Circuit-Breakers". Petroleum and Chemical Industry Conference Europe Conference Proceedings (PCIC EUROPE). Rome: IEEE.

[11]. Sankaran, C. (2002). "Power Quality". CRC Press LLC. Online source, date accessed: 23th November, 2014. Available at https://www.fer.unizg.hr/_download/repository/**Power_Quality**.pdf

[12]. ANSI/IEEE C57.12.80-1978 (R1987), American National Standard Terminology for Power and Distribution Transformers.

[13]. ANSI/IEEE C57.12.91-1979, American National Standard Test Code for Dry-Type Distribution and Power Transformers.

[14]. ECG. (2012). "Electricity Company of Ghana-Ghana Energy Development & Access. Accra- Planning Manual": *Electricity Company of Ghana, Engineering Directorate*