Impact Of Current Harmonics Emanating From Single Phase Loads On Low Voltage Network And Distribution Transformers- Case Study

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***Abstract*—The past few decades have experienced considerable changes in single phase loads in terms of their power demand magnitude and appliances characteristic. The main difference between single phase loads of today and that of two to three decades ago is penetration of electronic appliances with switch mode power supply such as computing devices, mobile chargers, audio-visual, air conditioner, energy saving bulbs (CFL) and electronic/ digital power system protection relays. These new modern single phase equipment generate current harmonic distortions which stream back to the low voltage distribution network. The impact of harmonic distortions in power system are deleterious such as loss of life of distribution transformers, erroneous recording of energy meter, and over-loading of neutral conductor among other serious consequences. Most of countries daily power demand report shows that the residential loads constitute up-to 60% of the total connected loads. In this regards, their effects on power system cannot be ignored/ assumed.**

Primarily, energy plays a critical role in development of a country economy. Therefore, provision of good quality, adequate, sustainable, cost effective and affordable energy for social – economical development is paramount. In recent time, loss of distribution transformers prematurely has contributed to myriad outcry of power users and high cost of operational and maintenance (O&M) costs to power utilities.

This study investigated the level of current harmonic distortions of various dominant single phase loads and harmonic levels at secondary side of the distribution transformers. It involved logging of power quality analyzer at point of common coupling (PCC) of domestic premises and low voltage side of distribution transformer respectively. From the study, it was found out that TV- CRO generated the highest total current harmonic distortions (93.7%) among all the analyzed domestic non-linear loads. The transformer supplying electronic devices at primary substation was found to have high harmonic eddy current losses and other stray losses. Distribution transformers with K-factor great than 1 are proposed to be installed at primary substations for local power supply.

Keywords—Distribution Transformer, Total Harmonic distortions, non-linear loads

I. INTRODUCTION

Power quality has recently raised great concerns. This has been primarily due to newer- generation load equipment with microprocessor- based controls and power electronic devices which are more sensitive to power quality variations than were equipment used in the past 20 -30 years. Further to this, end users have become aware of power quality issues such as transients, harmonic pollution, voltage interruptions, voltage swell/dips hence challenging power utilities to improve the quality of power delivered. Among the listed power quality issues, voltage interruptions have been identified as the most common power quality that causes myriad outcry to the power users. However, harmonic distortion which is a complex wave consisting of a series of sinusoidal waves whose frequencies are multiples of the frequency of basic wave, have been least considered and investigated despite causing serious negative impact on low voltage distribution network. The profound effects of harmonic distortions on low voltage distribution are not well known, (although savings from use of small non – linear domestic loads are known). One of characteristic of harmonic distortion is it streams back to power utility through service conductor (this conductor has less impedance relative to the other loads), hence affecting the neighboring power end users.

Sources of harmonic distortions in low voltage distribution network are numerous. The common well known sources of the harmonics are loads with non-linear v-i characteristics. The loads can be at domestic or large power end users. Some of non-linear domestic loads include but are not limited to TV sets, CPU and monitors, phone chargers, refrigerators, fans with electronic regulator, CFL lamps, washing machines, hot water with electronically controlled systems, water pumps, air conditioners, driers, microwave, UPS. On the other hand, in large power consumers, sources of harmonic distortions include power electronic converters (Adjustable Speed Drives, High Voltage DC-links, Static Var Compensators (SVCs), STATCOMs), rotating machines (salient pole synchronous machine) and transformers (due to non-linear magnetization core).

It is worth noting as per author of reference [2] who found that harmonic current injected by domestic loads are usually too small to cause significant distortion in distribution networks. However, when operating in large numbers, the accumulative effects have the capability of causing serious harmonic distortion levels. The main profound effects are over-loading of neutral conductors and additional losses on distribution transformer which could result to reduction of loss of life of distribution transformer. Failure of distribution transformer is devastating and costly experience because it causes an outage to the area the transformer is supplying electricity. In the past, distribution transformers used to serve for more than forty-five years [3]. In recent years, many distribution transformers fail even a few years after commissioning. It is for this reason that many studies are being carried out to investigate the main causes of the distribution transformers premature failure (loss of life). In Kenya for instance, the failure rate is approximately 10-12% per annum which is far above the failure rate of 1-2% in the developed countries [4].

It has been noted that due to relative low cost of distribution transformers (as compared with power transformers), very little effort is made by utility to find out the root cause of transformer failure. Lack of investigating the root cause, could be attributed to one of the reason why more failures happen immediately or within a very short period after replacing a faulty transformer [4], [5]. One of the main cause of the premature transformer failure is breakdown of dielectric insulation materials; transformer oil and insulating paper (solid insulation).

The study has shown that temperature rises cause the insulation life to decrease while moisture acting as catalyst. The transformer rise temperature can be as result of loads supplied by the transformer and/ or harmonics generated by non-linear loads connected to the transformer [6], [9], [10], [14]. It's imperative to note that, harmonics elevates winding eddy losses (eddy and circulating currents) and stray losses. Research done by Jyotirmaya et al, 2014 reveals that 50% of thermal stress of transformer is due to harmonic distortions caused by non-linear loads [11].

From literature, transformer losses consist of no-load (core losses) and load losses [12][13],[15].

$$P_T = P_{LL} + P_{NL} \quad (1)$$

Where; P_{LL} = load losses, P_{NL}= No-load

Load losses consist of P_{dc} losses (I^2R_{dc}) and stray losses which are as result of electromagnetic fields in windings, core clamps and tank walls. Stray losses are composition of winding eddy current losses (caused by eddy current and circulating current) and structural part stray losses. No load loss is insignificant on distribution transformer hence usually assumed. The load losses can be written as;

$$P_{LL} = P_{dc} + P_{EC} + P_{OSL} \quad (2)$$

$$P_{TS}L = P_{LL} - P_{dc} \quad (3)$$

Where; P_{TSL}- Total stray losses ($P_{EC} + P_{OSL}$)

Eddy current losses include skin and proximity effects. Losses due to skin effect are directly proportional to eddy current and frequency squared (I^2f^2) [13].

$$P_{EC} = P_{EC\text{-}o} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 h^2 \quad (4)$$

Where;

P_{EC} – Eddy losses, $P_{EC\text{-}o}$ -Winding eddy-current loss at the measured current and power frequency, h_{max} – is the highest significant harmonic order, I_h – is rms current at harmonic of order h and I is the rms load current.

Other stray losses in transformers are caused by an internally induced voltage that result eddy current to flow in the ferromagnetic materials such as core, clamps and structural parts. The eddy losses increase at rate proportional to I^2 and not proportional to f^2.

The harmonic loss factor for stray losses that relate to transformer connections, structural parts is therefore expressed as [15]

$$POSL=POSL\text{-}R \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 h0.8 \quad (5)$$

Proximity effect is as result of current carrying conductor inducing current to a neighboring conductor. In distribution transformer, HV windings produce a flux density that cuts the LV windings inducing an emf that produces circulating or eddy current.

II. RESULTS AND DISCUSSION

A. *Current Harmonic Distortions From Single Phase Loads*

Harmonic distortions emanating from domestic non- linear loads were investigated using power quality analyzer at the point of common coupling (at domestic premise metering box). Each appliance was powered individually and current harmonic distortions was recorded. The researchers also supplied combination of different loads and repeated the procedure. The following were the findings.

Table 1a: Individual THDi generated

No	Device	THDi %
1	TV(CRO)	93.7
2	Video player	83.51
3	TV(Plasma)	82.15
4	Computer- desk top	80.16
5	TV Decoder	74.53
6	Radio	70.01
7	Laptop	68.01
8	Fluorescence Tube (F. Tube)	41.61
9	Microwave	34.62
10	Fridge	24.25

Table 1b. Combined loads THDi generated

No	Device	THDi%
1	TV (CRO)+Radio	86.79
2	Computer + TV (CRO)	71.06
3	Computer + Radio	60.08
4	TV (CRO)+laptop +F. Tube	25.34
5	TV (CRO)+decoder +F. Tube	9.43
6	**All devices connected**	**8.45**

From the table 1a, above, it is vivid that domestic loads draw current in pulses hence distorting the current waveforms (hence high THDi). It was noted that the old type TV (CRO- technology) generates more harmonic distortions vis-à-vis other types of domestic loads investigated. This could mainly due to improvement by manufacturers as they try to comply with stringent requirements of various power quality standards such as 61000-2-3-4 standards that defines the recommended harmonic distortions generated by low voltage supplied loads, IEEE 519 - 1996, IEC 1000-3-2 and ER G5/4 [4]. Further, reduction in total harmonic distortions was evidence when more loads were supplied at same common point as shown in table 1b. The cancellation effect was a result of phase angle differences of harmonic generated by each individual device. It is worth noting that same type of loads when are connected together have additive harmonic distortions effects while various types of non- linear loads supplied power together have damping effect on the total harmonic distortions [10]. This explain why is recommendable to have different non-linear loads supplied from same common power supply.

B. Harmonic Distortions at Secondary Side of Distribution Transformer

The researchers investigated the level of harmonic distortions at different sampled distribution transformers. The harmonic data were obtained after logging a power quality analyzer on secondary side (415V) of the transformer for two weeks with sampling rate set at five (5) minutes. The table 2 below depicts the findings.

Table 2: Distribution transformer secondary side harmonic distortion levels

Nature of loads	Rating of transformer (kVA)	Ave. loading (kVA)	THDv (%)	THDi (%)	2nd Harmonic		3rd Harmonic		5th Harmonic		7th Harmonic		9th Harmonic		11th Harmonic		13th Harmonic	
					Value (%)	Current (A)	Value (%)	Current (A)	Value (%)	Current (A)	Value (%)	Current (A)	Value (%)	Current (A)	Value (%)	Current (A)	Value (%)	Current (A)
Commercial	200	124.8	**2.38**	**10.25**	4.61	3	10.37	5.1	5.5	2.4	4.75	2.3	3.85	1	3.39	<1	2.37	<1
Substation Electronic devices	100	6.7	**2.7**	**14.0**	2.8	0.19	10.92	1.8	10.05	1.9	6.63	1	3.7	0.2	1.85	<0.2	0.67	<0.2
Domestic loads (Rural)	100	17.6	**5.8**	**38.44**	16.12	0.46	44.4	2.08	17.89	0.66	10.1	0.48	8.3	0.26	0.94	<0.2	0.24	<0.2
Domestic loads (Urban)	100	10.4	**3.01**	**28.58**	5.55	0.38	22.21	4.7	13.3	1.4	4.64	0.7	3.02	0.6	1.58	<0.1	0.84	<0.1
Supplying office loads	100	15.2	**2.5**	**13.26**	5.35	2.8	13.12	6.46	6.82	4.7	5.11	2.5	9.63	2.2	4.32	5.7	2.91	2.52

Where;
THDi-current total harmonic distortion, THDv-Voltage total harmonic distortion

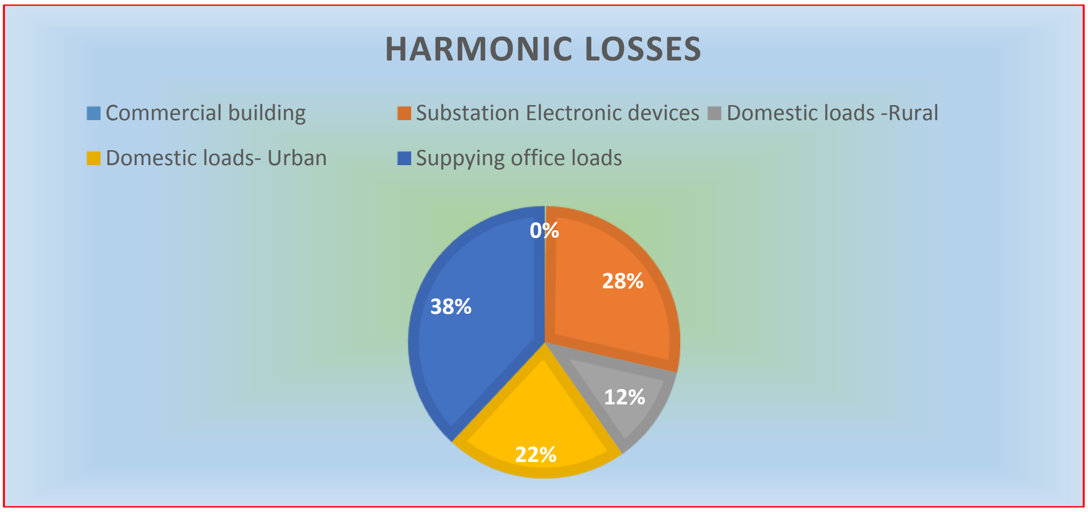
From above table 2, except transformer installed at rural area the THDv was slightly above admissible level, others THDv were well within the allowable limit (< 5%). Worth point out is that individual current harmonic distortions level was noted they diminishes as frequencies (order) increases. In addition, the more the transformer was loaded, the lower the THDi observed. This was as result of damping (cancellation) effects caused by different harmonic level generated by various loads with difference phase angles. It is imperative noting that resistive loads provide the highest harmonic attenuation.

Using equations (4) and (5), the losses due to eddy current and other stray losses were as shown in table 3 below.

Table 3: Transformer losses due to presence of current harmonic distortions

Nature of loads	2nd	3rd	5th	7th	9th	11th	13th	Pos-losses (W)	Pec-Losses (W)	Grand Total (W)
Commercial building	0.02	0.07	0.02	0.03	0.01	0.01	0.00	**0.15**	**1.00**	**1.15**
Substation Electronic devices	0.32	2.64	4.14	3.25	1.09	1.02	0.91	**13.37**	**125.90**	**139.26**
Domestic loads - Rural	0.30	1.37	0.82	0.83	0.62	0.59	0.60	**5.13**	**52.25**	**57.38**
Domestic loads- Urban	0.39	4.00	2.28	1.72	1.85	0.52	0.50	**11.25**	**95.22**	**106.47**
Supplying office loads	0.56	1.51	1.77	1.40	1.54	3.87	2.30	**12.96**	**173.93**	**186.88**

The following chart 1 depicts the harmonic distortions loss for each of the transformer.



From table 3 and chart 1, it was noted that office loads causes high losses within the transformer followed by domestic loads in urban area. This is mainly because of the having similar non-linear loads being supplied from same point (computers, monitors, printers and laptops) which have additive harmonic effects contrary to when the transformer is loaded with different loads. This explain why most of the transformers are failing at urban area and at primary substations. It is pertinent noting that even harmonics contribute least on transformer current harmonic eddy current losses and other stray losses.

III. CONCLUSION

This paper has analysed various non-linear loads and the impact they have on low voltage distribution network particularly on distribution transformers. It has been noted that substation electronic single phase loads generate high harmonic losses vis-á-vis other types of single phase loads harmonic power losses were investigated. The TV -CRO was found to have 93.7% THDi which was highest compared with other domestic non loads such as microwave, Plasma TV etc. Further research is proposed to establish the expectant life of distribution transformers installed at different locations such as coast area, area with high lightning activities, urban and rural areas. Distribution transformer with K-factor greater than 1 is recommended for primary substation local supplies transformer (11/0.415kV) which are designed specifically to withstand high harmonic related losses.

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