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Evaluation of Harmonics & Its Effect on Transformer Load Loss

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Abstract
The increased use of non linear modern loads that use high frequency switching generate harmonics in distribution system. The existence of high level harmonics causes several undesirable effects such as transformer overheating, increase of running losses, increase in loading profile of transformer, nuisance tripping of protection devices and loss of life of transformer. In this paper evaluation of the harmonics spectrum level of distribution transformer feeding combination of non linear and linear loads and its effect on the capacity reduction and power factor. The harmonics spectrum data obtained using power quality analyzer (PQA) is compared against IEEE standard and possible solution is recommended. Based on harmonics spectrum data, increase in total load current and power loss are respectively 14.5 % and 7.2%
Keywords: Harmonics, Distribution transformer, Power loss.

1. INTRODUCTION

Harmonics in electrical power system is becoming a major concern for electric utility company and consumers. It is produced by power electronics based equipment which are called non-linear loads. Examples of nonlinear loads are computers, compact fluorescent lamp and television in residential while variable speed drives, inverters and arc furnaces are mostly common in industrial areas. Increasing numbers of these loads in electrical system for the purpose of, improving energy efficiency, has caused an increase in harmonics pollution. These loads draw non-sinusoidal current from the system [1]. The harmonic currents that are injected in to the system cause voltage drop at distribution networks and cause voltage distortion as well. A particular group of harmonics that draws special attention is a triplen harmonics, which is odd multiple of third harmonics. This is so because unlike fundamental frequency component, triplen frequency components coincide in time and phase and produce a neutral current larger than phase current[2]

The undesirable effects that harmonics have on distribution transformer include voltage distortions, increase of total current, increased operational loss(increase of winding loss), increased heating which leads to insulation fatigue of coils and malfunctioning of sensitive power system equipment such as capacitor banks. Resonance is another problem which is caused by harmonics. This occurs when harmonic current produced by nonlinear loads interacted with impedance of the power system and produces high harmonic current.

2.Harmonic distortion Limits

Institute of Electrical and Electronics Engineers (IEEE) has come out with standards and guidelines regarding harmonics. One of the standards, IEEE Standard 519-1992, provides comprehensive recommended guidelines on investigation, assessment and measurement of harmonics in power system. The standard includes steady state limits on current harmonic and harmonic voltages at all system voltage levels. The limit was set for a steady state operation and for worst case scenario. [3]

Table.1: Harmonic Current distortion level in percent of total load current (system voltage range between 120V to 69kV)

I_{SC}/I_L	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7	6.0	2.5	1.4	20.0
TDD - Total demand distortion						
h- odd harmonics						
Isc- Maximum short circuit current						
I_L - Maximum fundamental load current						

Table.2: Harmonic Voltage distortion limits

Bus voltage at Point of common coupling (PCC)	Individual voltage Distortion	Total voltage Distortion
≤69kV	3.0	5.0
69kV to 161kV	1.5	2.5
69kV & above	1.0	1.5

Another international standards and conformity assessment body, International Electro technical

Commission (IEC), produced a standard, IEC 61000-3-6, which also provides guidelines to address harmonics issue with sets of steady state limits. Both standards are in common where the limits were derived based on a basic principle of insuring voltage quality and shared responsibility between utility and customer (Halpin, 2005). Both lay the responsibility on consumer to limit the penetration of current harmonic into power system while utility company is responsible to limit harmonic voltage at point of common coupling (PCC). According to IEEE definition, point of common coupling is a point anywhere in the entire system where utility and consumer can have access for direct measurement and the indices is meaningful to both.

Example of steady state harmonic voltage limit from IEEE Std. 519-1992 at PCC for medium voltage level (< 69 kV) is 5% THD and 3% individual voltage distortion. In reality, harmonic is time-variant and it changes over time due to several factors. Both standards recognize this condition and allow the limits to be exceeded for short duration. IEC has provided a set of time-varying limits based on percentile over a period of time i.e. 95th and 99th for very short time (3 second) and short time (10 minute) aggregate measurements.

3. Harmonic Mitigation

Several methods of mitigating harmonics have been developed over the years. The most common method is using filter, either passive or active. Passive filter block certain harmonic bandwidth while active filter injects current into the system to cancel the current harmonic waveforms. Both methods have their advantages and disadvantages, for example, advantage of passive filter is easy to design and active filter can monitor many frequencies simultaneously while disadvantage of passive filter is bulky in size and active filter is costly (Izhar et. al., 2003). Harmonic filters are useful and practical to be implemented by consumer near the proximity of the non-linear load at the low voltage system. Another method which is normally used by consumers is using phase cancellation method using twelve pulse converters instead of six pulse converters.

Similar application using filters for utility at higher voltage level such as distribution network requires extensive economic consideration. This is due to the size and cost of the equipment while most of harmonic pollutant is caused by consumer. There is little study on a feasible and cost effective means for utility to mitigate harmonic, especially harmonic voltage. A study was conducted on method using shunt harmonic impedance (Ryckaert et. al., 2004) which can act like a central damper to reduce harmonic at distribution network. This method is considered to be less expensive compared to active filter. The method uses power electronic to emulate resistive behavior for harmonic. However, the method is still under further study. Currently, all harmonic mitigation techniques involve equipment required to be installed on the system. There is yet a study on using other factors which can affects harmonic voltage distortion such as network impedance. Optimizing network impedance to mitigate harmonic can be cost effective for utility to apply. Because of mitigating harmonic is expensive, many utility company have resorted in imposing penalty to consumer for injecting current harmonic above the standard steady state limit into the system. This process requires method on determining harmonic contribution by the consumers (Li, et. al., 2004) and the equipment need to be installed at all consumers' feeder which is very costly.

4. Components of transformer losses & effects of harmonics on them

Transformer losses are categorized as no load losses and load losses. The no load losses are excitation losses caused by eddy currents in magnetic core & hysteresis loss of the core.

$$P_{\text{no-load}} = P_{\text{core eddy}} + P_{\text{hysteresis}} \qquad (1)$$

Since the no load losses are dependent on excitation voltage and the total harmonic voltage distortion (THDv) in most power system falls below 5% and the magnitudes of harmonic voltages are near to 2 to 3% of the fundamental component, the extra no load loss caused by voltage harmonics is insignificant.[3] But when the voltage distortion level is large enough, the no load loss can be evaluated by using the following equation[4]

$$P = P_M * \left[P_h + P_{ec} \left(\frac{V_{\text{hrms}}}{V_{\text{rms}}} \right)^2 \right] \; (2)$$

Where, P & PM are no load losses at distorted and sinusoidal voltages, Ph & Pec are hysteresis and eddy current losses, V hrms & Vrms are the RMS values of distorted and sinusoidal voltages respectively[6]

The load losses, which are also known as impedance losses are sum of I2R (ohmic loss) and stray loss. The total stray loss is subdivided into winding stray loss(caused by eddy current in the strands of winding conductor) and other stray losses (caused by time variation of leakage flux in the structural parts such as tank walls, core clamps, etc.

$$P_{\text{load}} = I^2R + P_{\text{coil eddy}} + P_{\text{OSL}} \qquad (2)$$

Existence of harmonics causes an increase in both ohmic loss and stray loss and these losses under harmonic current can be evaluated by using the following formulae:

$$P_{DC} = P_{DC-R} * \sum_{h=1}^{h=max} \left(\frac{I_h}{I_R}\right)^2 \quad (3)$$

where P_(DC-R)is the rated ohmic loss and IR is the rated fundamental frequency current of transformer.
The winding eddy current loss in the case of transformer supplying non linear loads can be given by the following equation:

$$P_{EC} = P_{EC-R} * \sum_{h=1}^{h=max} h^2 \left(\frac{I_h}{I_R}\right)^2 \quad (4)$$

where P_(EC-R)is the rated eddy current loss at rated fundamental frequency current of transformer.
The winding eddy current losses in the case of harmonic rich loads should be multiplied by harmonic loss factor(HLF) to correct the loss value[7]

$$H_{LF} = \frac{\sum_{h=1}^{h=max} h^2 \left(\frac{I_h}{I_R}\right)^2}{\sum_{h=1}^{h=max} \left(\frac{I_h}{I_R}\right)^2} \quad (5)$$

The variation of other stray losses in the presence of harmonics can be evaluated from the following equation:

$$P_{OSL} = P_{OSL-R} * \sum_{h=1}^{h=max} h^{0.8} \left(\frac{I_h}{I_R}\right)^2 \quad (6)$$

The loss correction factor for other stray losses is expressed in a similar way as it is for winding eddy current.

$$H_{LF-OSL} = \frac{\sum_{h=1}^{h=max} h^{0.8} \left(\frac{I_h}{I_R}\right)^2}{\sum_{h=1}^{h=max} \left(\frac{I_h}{I_R}\right)^2} \quad (7)$$

5. Methodology

This research makes use of measurement technique to determine the total harmonic current distortion & total harmonic voltage distortion level. Power quality analyzer (PITE3561) is connected to the distribution transformer secondary terminal, which is treated as point of common coupling between utility & end user. Measurement is carried out at peak load time, between 10:00 AM local time & 5:00 AM local time for five days. The measured voltage, current, active power, reactive power & apparent power values for five days are manipulated to determine the RMS values. Based on the data from measurement and name plate readings, total current distortion level, total voltage distortion level, additional winding loss, eddy current loss due to harmonics and capacity reduction due to presence of harmonics are determined. The following table gives the data of the transformer under study:

6. Result and Discussion

6.1 Nameplate & Calculated parameters of transformer

The distribution transformer under study is an oil filled one 90% 0f load loss is assumed to be ohmic loss and 10% of the load loss is assumed to be total stray loss. Furthermore, 33% stray loss is assumed to winding eddy current loss and 67% of total stray loss is other stray loss[

Table3: Data of distribution transformer

Parameter	Rating	Remark
V1/V2	15KV/0.4KV	Name plate data
Capacity	315KVA	Name plate data
%Impedance	4.50%	Name plate data
MVA_{SC}	7MVA	Calculated
I_{SC}	10115A	Calculated
I_L	141.1A	Measured
I_{SC}/I_L	71.7	Calculated
$P_{No\ load\ loss}$	0.688kw	Name plate data
$P_{Load\ loss}$	4.3kW	Name plate data
P_{dc}	3870W	Calculated
P_{TS}	430W	Calculated
I_R	455A	Calculated
Load fraction	31%	Calculated

From Table3, it can be seen that the short circuit ratio (ISC/IL) is between 50 & 100, which indicates that the TDD of 12% can be applied. The following tables show the harmonic voltage levels and harmonic current levels of the distribution transformer as they observed during measuring.

6.2. Measured values Harmonic Voltages & Currents

Table4: Harmonic Voltage Level

HAR. Testing Chart							
Test Voltage: Max= 230.6V,Min=229.6V, Ave = 230.2V							
Test Current: Max =143.2A,Min =138.8A,Ave = 141.0A							
Harmonic Order	VA		VB		VC		Average
	Test Value	Remark	Test Value	Remark	Test Value	Remark	
THD	3.02	Safe	2.07	Safe	3.12	Safe	2.7
H1(%f)	100	---	100	---	100	---	100
H2(%f)	0.06	Safe	0.08	Safe	0.05	Safe	0.06
H3(%f)	0.17	Safe	0.15	Safe	0.17	Safe	0.16
H4(%f)	0.09	Safe	0.06	Safe	0.01	Safe	0.05
H5(%f)	2.97	Safe	2.72	Safe	3.04	Safe	2.91
H6(%f)	0.11	Safe	0.09	Safe	0.06	Safe	0.08
H7(%f)	0.45	Safe	0.44	Safe	0.55	Safe	0.48
H8(%f)	0.04	Safe	0.02	Safe	0.03	Safe	0.03
H9(%f)	0.1	Safe	0.09	Safe	0.07	Safe	0.08
H10(%f)	0.06	Safe	0.03	Safe	0.04	Safe	0.04
H11(%f)	0.09	Safe	0.06	Safe	0.06	Safe	0.07
H12(%f)	0.02	Safe	0.04	Safe	0.05	Safe	0.03
H13(%f)	0.07	Safe	0.011	Safe	0.012	Safe	0.031
H14(%f)	0.03	Safe	0.02	Safe	0.03	Safe	0.02
H15(%f)	0.03	Safe	0.04	Safe	0.04	Safe	0.036
H16(%f)	0.03	Safe	0.01	Safe	0.02	Safe	0.02
H17(%f)	0.02	Safe	0.05	Safe	0.03	Safe	0.03
H18(%f)	0.01	Safe	0.03	Safe	0.02	Safe	0.02
H19(%f)	0.02	Safe	0.03	Safe	0.04	Safe	0.03
H20(%f)	0.03	Safe	0.03	Safe	0.04	Safe	0.033
H21(%f)	0.01	Safe	0.03	Safe	0.02	Safe	0.02
H22(%f)	0.01	Safe	0.01	Safe	0.02	Safe	0.013
H23(%f)	0.02	Safe	0.03	Safe	0.01	Safe	0.02
H24(%f)	0.011	Safe	0.08	Safe	0.08	Safe	0.057
H25(%f)	0.011	Safe	0.08	Safe	0.08	Safe	0.057

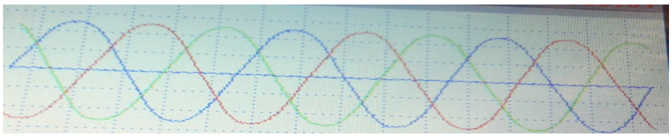

Fig.1:Voltage Wave shape

Table5: Harmonic Current Levels (Measured values)

HAR. Testing Chart							
Test Voltage: Max=230.6V,Min=229.6V, Ave = 230.2V							Average
Test Current: Max =143.2A,Min =138.8A,Ave = 141.0A							
HAR. Current Testing Table							
Harmonic order	IA		IB		IC		
	Test Value	Remark	Test Value	Remark	Test Value	Remark	
THD	7.61	Safe	7.33	Safe	8.03	Safe	7.65
H1(%f)	100	---	100	---	100	---	100
H2(%f)	0.11	Safe	0.1	Safe	0.15	Safe	0.12
H3(%f)	1.46	Safe	1.54	Safe	3.64	Safe	2.23
H4(%f)	0.21	Safe	0.26	Safe	0.18	Safe	0.21
H5(%f)	7.15	Safe	6.69	Safe	6.79	Safe	6.876
H6(%f)	0.05	Safe	0.05	Safe	0.03	Safe	0.043
H7(%f)	1.8	Safe	2.17	Safe	1.66	Safe	1.87
H8(%f)	0.03	Safe	0.05	Safe	0.05	Safe	0.043
H9(%f)	0.19	Safe	0.09	Safe	0.38	Safe	0.22
H10(%f)	0.03	Safe	0.04	Safe	0.03	Safe	0.033
H11(%f)	0.79	Safe	0.84	Safe	0.96	Safe	0.863
H12(%f)	0.05	Safe	0.04	Safe	0.03	Safe	0.04
H13(%f)	0.53	Safe	0.83	Safe	0.68	Safe	0.68
H14(%f)	0.02	Safe	0.02	Safe	0.03	Safe	0.023
H15(%f)	0.07	Safe	0.19	Safe	0.06	Safe	0.106
H16(%f)	0.02	Safe	0.02	Safe	0.02	Safe	0.02
H17(%f)	0.17	Safe	0.28	Safe	0.28	Safe	0.243
H18(%f)	0.04	Safe	0.04	Safe	0.05	Safe	0.043
H19(%f)	0.21	Safe	0.22	Safe	0.27	Safe	0.233
H20(%f)	0.02	Safe	0.04	Safe	0.03	Safe	0.03
H21(%f)	0.04	Safe	0.16	Safe	0.08	Safe	0.09
H22(%f)	0.13	Safe	0.15	Safe	0.14	Safe	0.14
H23(%f)	0.13	Safe	0.19	Safe	0.15	Safe	0.15
H24(%f)	0.11	Safe	0.08	Safe	0.08	Safe	0.09
H25(%f)	0.06	Safe	0.12	Safe	0.09	Safe	0.09

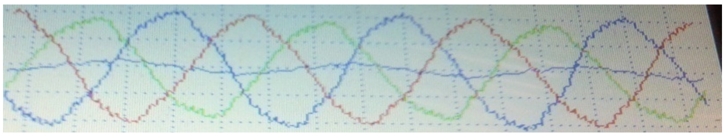

Fig.2: Current wave forms

Based on Table 4. &Table5, the average total harmonic current distortion(THDi) and average total harmonic voltage distortion(THDv) are 7.65 and 2.7 respectively.

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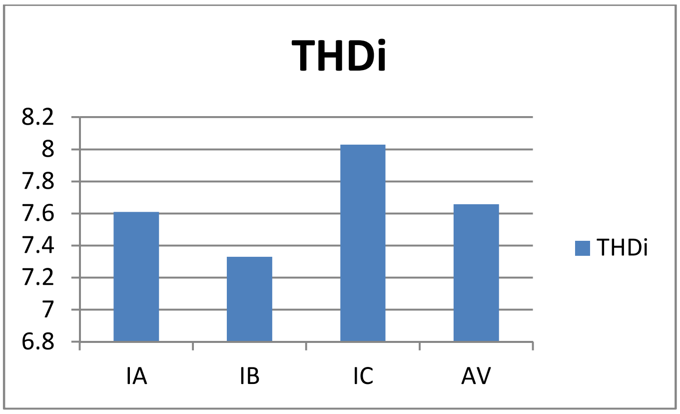

Fig.3: Average total harmonic current distortion

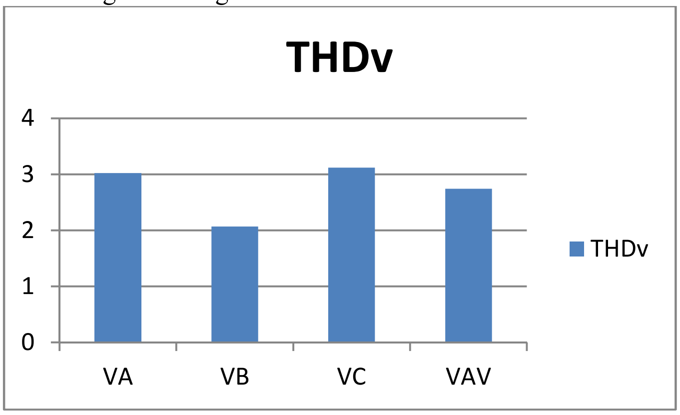

Fig.4: Average total harmonic voltage distortion

6.3. Harmonic Loss factor calculation:

The harmonic loss factor for winding eddy current loss(FHL) and other stray losses (FH-OSL) can be obtained by using the data found in table5. The values are 1.56 & 1.72 respectively. By using these values, additional loss due to the presence of harmonics is calculated as shown below.

Table6: Additional loss due to harmonic current

Type of Loss	Rated load Loss(W)	Loss-1 (W)	Loss-h (RMS)(W)
Ohmic Loss	3870	372	373.8
Winding Eddy current loss	142	13.6	21.4
Other stray Loss	288	27.8	47.85
Total Load Loss	4300	413.23	443.1
Additional Loss incurred	7.2%		

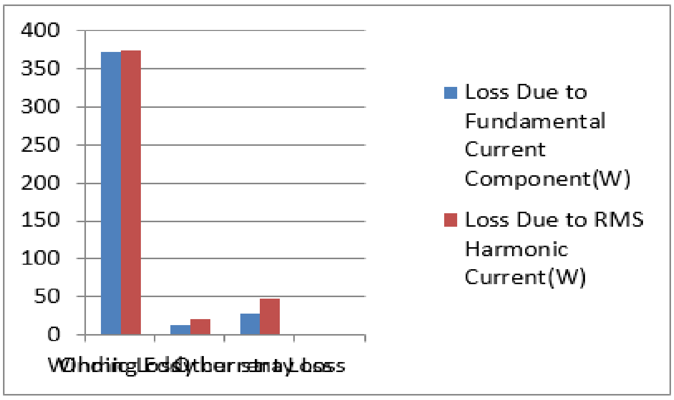

Fig.5: Loss due to fundamental current & Harmonics

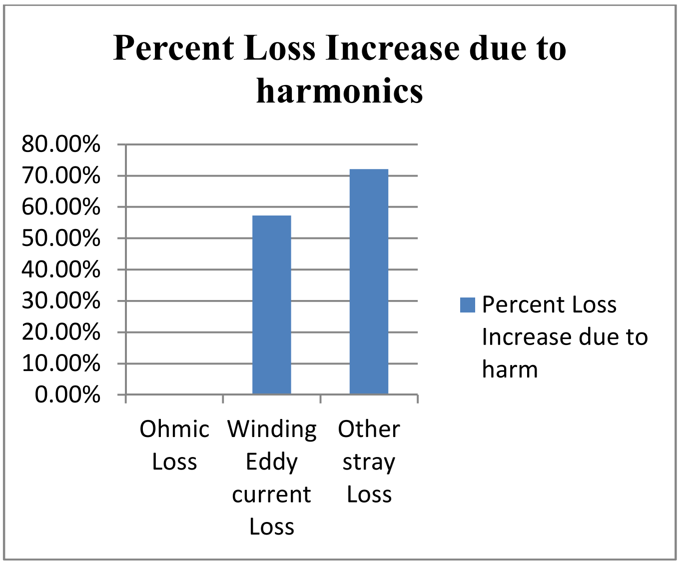

Fig.6: Percent Loss increase due to harmonics

7. Conclusion

Evaluation of harmonics & its effect on transformer load loss was done in this research. The data analysis result shows that the total voltage harmonics of the transformer under study is 2.7,which is well below the IEEE recommended harmonic voltage index of 5%. However, the measurement result showed that the harmonic voltage indices for three phases is different, the largest value for phase A& phase C and the smallest for phase B. On the other hand, the harmonic current distortion index is 7.65,which is also below the IEEE recommended value of 12%. However, if the loading condition is changed, there is a tendency for the harmonic current distortion to go out of the recommended value. Regarding the additional loss due to harmonics, the analysis result shows that loss is increased by 7.2%

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Annex1.
1:Distribution Transformer under study