Distribution Transformer Losses Evaluation under Non-Linear Load

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Abstract— **Harmonic effect on power system component and load are one of the important considerations when evaluating the impact of harmonics. Transformers are one of the component and usually the interface between the supply and most nonlinear load. With the increasing use of nonlinear load the harmonic problem become worse. The increased losses in the transformer due to the harmonic distortion can cause excessive winding loss and abnormal temperature rise. This paper presents the analysis and evaluation of distribution transformer losses under non-linear load. In this study the harmonic data logging was conducted in the commercial building and the losses caused by harmonic in distribution transformer were calculated. The life of the transformer also can be estimated from the simulation results. The results show that an increase in the current harmonic distortion will increase the transformer losses and hence decreased it life expectancy.**

Keywords—harmonic distortion, transformer losses, real life of transformer, harmonic loss factor

I. INTRODUCTION

Harmonic in power system has increased substantially due to the increasing of non linear load in recent years. Transformers are usually designed for utilizing at the rated frequency and linear load. Nowadays with the present of nonlinear load, transformer leads to higher losses and reduction of the useful life. The increased losses due to harmonic distortion can cause excessive winding loss and abnormal temperature rise. If the transformer cannot be operated up to its standard lifetime, there will be an economic loss.

The measurement of a transformer's losses and calculation of its efficiency is applied in the power and distribution transformer. Three methods of estimating harmonic load content are; the crest factor, harmonic factor (percent total harmonic distortion- %THD) and K-Factor. The first two methods are most common methods of harmonic estimation but limited because the harmonic frequencies are not considered, and a K-factor is the most complex [1]. Increased in harmonic distortion component of a transformer will result in additional heating losses, shorten insulation lifetime, higher temperature and insulation stress, reduce power factor, lower productivity and capacity and lack of performance of the system [5].To prevent these problems, rated capacity of transformer supplying non-linear load must be reduced [2]. Manufacturer of distribution transformer have developed a rating system called K-Factor, a design that is capable of withstanding the effects of harmonic load currents [3].

Transformers are one of the component and usually the interface between the supply and most non-linear loads. Harmonic voltage increase losses in its magnetic core while harmonic currents increased losses in its winding and structure [6]. In general, harmonics losses occur from increased heat dissipation in the windings and skin effect both are a function of the square of the rms current, as well as from eddy currents and core losses [7]. This extra heat can have a significant impact in reducing the operating life of the transformer insulation. The increased of eddy current losses that produced by a non-sinusoidal load current can cause abnormal temperature rise and hence excessive winding losses. Therefore the influence of the current harmonics is more important. Many works have been developed about the harmonic effect on power transformer loss of life [4,8-12]. However, these works did not take into consideration the standards of harmonics. In this study, harmonic data at distribution transformer of the commercial building have been measured. This study will investigate on the transformer loss of life based on the Malaysian standard on harmonics [15]. The organization of this paper is as follows: Section II gives a definition of harmonic, section III presents transformer losses, section IV shows the calculation of harmonic loss factor, section V describe transformer's loss of life calculation, section VI explain on harmonic data logging, section VII gives the result and analysis and finally this paper was conclude in section VIII.

II. HARMONIC DEFINITION

A harmonic component in an AC power system is defined as a sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple of the fundamental frequency of the system. [7]. The major source of harmonics is from the three categories of equipment, which are power system equipment, industrial loads and residential loads. Harmonic currents are generated to a small extent and low distortion level by generation, transmission and distribution equipments and to a larger extent by the industrial and domestic loads.

IEEE 519:1992 [16] also identifies the major source of harmonics in power system. The harmonic sources describe in this standard include power converters, arc furnaces, static VAR compensator, inverters of dispersed generation, electronic phase control of power, switched mode power supplies and pulse wide modulated drives. This standard concludes with recommendation for evaluating new harmonic source by measurement and detailed modeling and simulation studies. It provides several examples to illustrate how this recommendation can be implemented effectively in several practical systems.

III. TRANSFORMER LOSSES

Transformers are designed to deliver the required power to the connected loads with minimum losses at fundamental frequency. Transformer losses are generally classified into no load losses and load losses as shown in eqn. 1 [2, 3, 8].

$$P_T = P_{NL} + P_{LL} \tag{1}$$

Where,
P_T = total loss, watt,
P_{NL} = no load loss, watt,
P_{LL} = load loss, watt

The no load loss or excitation loss are the losses due to the voltage excitation of the core and magnetic hysteresis and eddy currents. The load loss or impedance loss is subdivided into I^2R loss and stray loss caused by electromagnetic flux in the winding, core, core clamps, magnetic shield, enclosure or tanks walls, etc [3,8]. Thus, the total stray loss is subdivided into winding stray loss and stray loss in components other than the windings (P_{OSL}). The windings stray loss includes winding conductor strand loss and loss due to circulating currents between strands or parallel winding circuits. The total load loss can be stated as follows:

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

Where,
P_{I^2R} = loss in the winding
P_{EC} = eddy current loss
P_{OSL} = other stray loss

The rated losses of the transformer can be calculated using the data provided. Initially, the rated current at the primary and secondary sides are calculated as follows;

$$I_{1-rated} = \frac{S(kVA)}{\sqrt{3}V_1} \tag{3}$$

$$I_{2-rated} = \frac{S(kVA)}{\sqrt{3}V_2} \tag{4}$$

The I^2R losses are calculated as in eqn. 5,

$$P_{I^2R-rated} = K\left[I_{1-rated}{}^2 R_1 + I_{2-rated}{}^2 R_2\right] \tag{5}$$

Where
K = 1.0 for single-phase transformers
= 1.5 for three-phase transformers

$$P_{LL-rated} = P_{I^2R-rated} + P_{TSL-rated} \tag{6}$$

$$P_{TSL-rated} = P_{EC-rated} + P_{OSL-rated} \tag{7}$$

Where,
I_1 = current in primary side of transformer,
I_2 = current in secondary side of transformer
R_1 = primary dc resistance
R_2 = secondary dc resistance
P_{TSL} = total stray loss

Based on the IEEE Standard [13] for the oil type transformer, the eddy current loss is assumed to be about 0.33 of the total stray losses.

$$P_{EC-rated} = 0.33 P_{TSL-rated} \tag{8}$$

$$P_{OSL-rated} = P_{TSL-rated} - P_{EC-rated} \tag{9}$$

IV HARMONIC LOSS FACTOR

Harmonic loss factor, F_{HL} is a key indicator of the current harmonic impact on the winding eddy loss and other stray loss. The harmonic loss factor is normalized to either the fundamental or the rms current.

F_{HL} for winding eddy current is the ratio of the total eddy current losses due to the harmonics, to the eddy current losses at the power frequency. The F_{HL-STR} is the ratio of the other stray loss due to the harmonic to the other stray loss at power frequency. The eddy current loss is increased by a factor of F_{HL} and the other stray loss are increased by a factor of F_{HL-STR} in the presence of harmonics. The transformer load losses in non-sinusoidal condition as shown in eqn. (10);

$$P_{LL} = P_{I^2R-rated} + F_{HL} P_{EC-rated} + F_{HL-STR} P_{OSL-rated} \tag{10}$$

This factor is calculated by the following equations [13]

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2} \tag{11}$$

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2} \tag{12}$$

Where,
F_{HL} = harmonic factor for eddy current loss,
$F_{HL\text{-}STR}$ = harmonic factor for other stray loss
The per unit load losses and rated per unit eddy current loss is given by the expression below [13]

$$P_{LL-pu} = P_{LL-rated}(pu)^2 \times \sum_{h=1}^{h=h\max} \left(\frac{I_h}{I_1} \right)^2 \quad (13)$$

$$P_{EC-rated-pu} = \frac{2.8(P_{EC-rated})}{1.5(I_{2-rated})^2 R_2} \quad (14)$$

Where,
h = harmonic order
h_{max} = maximum harmonic order
I_1 = rms current of fundamental component
pu = per unit quantities

V. TRANSFORMER'S LOSS OF LIFE CALCULATION

The transformer loss of life estimation is based on the deterioration rate achieved by insulating materials [8, 10, and 11]. About 50% of a transformer loss of life is caused by thermal stresses which are produced by the non-linear load current [10]. The hottest spot winding temperature is calculated as follows [8];

$$\theta_{TO} = \theta_{TO-rated} \left(\frac{P_{LL-C} + P_{NL}}{P_{LL-rated} + P_{NL}} \right)^{0.8} \quad (15)$$

$$\theta_g = (\theta_W - \theta_{TO-rated}) \left(1 + \frac{F_{HL}(P_{EC-rated\,pu})}{1 + P_{EC-rated\,pu}} \times P_{LL-pu} \right)^{0.8} \quad (16)$$

The hot spot temperature is;

$$\theta_H = \theta_{TO} + \theta_g + \theta_A \quad (17)$$

Where,
θ_{TO} = oil temperature rise,
θ_W = winding temperature rise,
θ_A = ambient temperature
θ_g = hottest spot conductor rise over top oil temperature,
θ_H = hot spot temperature

The relative aging factor, the loss of life and real life of a transformer can be expressed in the following manner [14];

$$F_{AA} = \exp\left(\frac{15000}{383} - \frac{15000}{\theta_H + 273} \right) \quad (18)$$

$$\%LOL = \frac{F_{AA} \times t \times 100}{normal\_insulation\_life} \quad (19)$$

$$Life(pu) = 9.8 \times 10^{-18} e^{\left(\frac{15000}{\theta_H + 273} \right)} \quad (20)$$

Real life = Life (pu) x normal insulation life or (21)
Real life = normal insulation life(year)/ F_{AA} (22)

Where,
F_{AA} = relative aging factor
%LOL = lost of life in percent
t = given time period

VI. HARMONIC DATA LOGGING

The power quality analyzer is used to log the harmonic data. The measurements were taken for two different buildings. The first case is at the faculty and the second case being the lecture hall building. The type of loads connected includes personal computers, fluorescent lamps, air conditioners, printers, photocopy machines LCD projectors and others. For both cases the data was logged for one week with intervals of five-minute. Optical cable for USB and Power Log software was used to transfer the data stored in the instrument to the computer. The logger was set to measure quantities such as frequency, voltage, current, total harmonic distortion, active power, reactive power, apparent power, voltage harmonic, current harmonic, true power factor and displacement power factor.

Table I shows the specifications of the distribution transformers and Table II shows harmonic current of the transformer load which are compared to the standards. The total harmonic distortion for Case 1 and Case 2 are 37.05% and 18.36% respectively. The daily curve or load per unit of the transformer is shown in Fig.1. The usage of the loads in the building are based on the duration of working hours at the buildings which is from 8.00 am to 10.30 pm for the library and for the office and lecture hall building the operating hours is from 8.00 am to 5.00 pm. The maximum per unit load achieved by the transformers are approximately 0.4 per unit and 0.7 per unit for Case 1 and Case 2 respectively.

TABLE I: THE CHARACTERISTICS OF DISTRIBUTION TRANSFORMER

	CASE 1	CASE 2
No Load Losses	2000 W	1600 W
Load Losses	25000 W	14570 W
Power (kVA)	1750	1500
Primary Voltage	11000 V	11000 V
Secondary Voltage	433 V	433 V
Winding Temperature Rise	65 °C	65 °C
Ambient Temperature	30 °C	30 °C
Normal Insulation Life	20.55 years	20.55 years

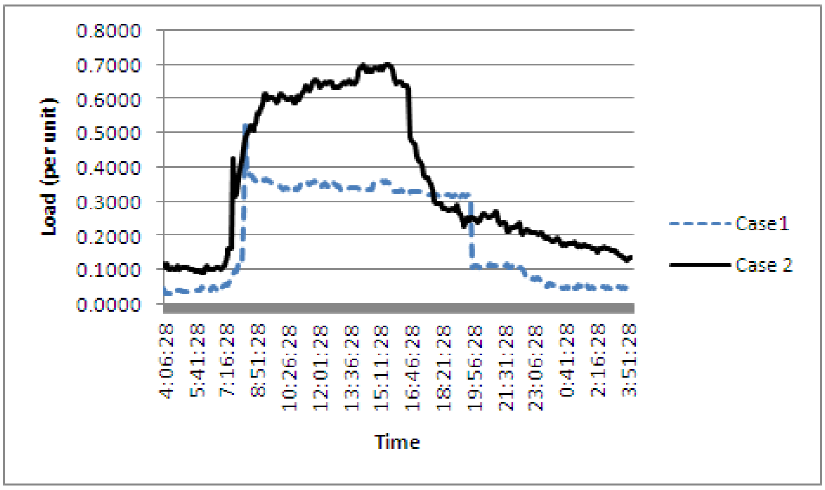

Figure 1: Daily load cycle of the transformer

TABLE II: HARMONIC DISTORTION FOR A TRANSFORMER LOAD COMPARE WITH THE STANDARD

Harmonic No.	**Harmonic current (A) (Case I)**	**Maximum Limit of MS 1555:2002(IEC TR 61000-3-4:1998)**	**Harmonic current (A) (Case II)**	**Maximum Limit of MS 1555:2002(IEC TR 61000-3-4:1998)**
3	302.1987	201.528	96.36	157.68
5	124.9287	99.831	74.168	78.11
7	87.1422	67.176	41.318	52.56
9	60.9249	35.454	29.93	27.74
11	30.1359	28.923	15.33	22.63
13	13.5285	18.66	12.994	14.6
15	13.1553	6.531	13.14	5.11

TABLE III: THE BREAKDOWN OF LOSSES IN DISTRIBUTION TRANSFORMER

Type of loss	**Rated losses(W)**	**Load losses (W)**	**Harmonic multiplier**	**Corrected losses (W)**
No load	2000	2000		2000
I^2R	8750	2488		2488
Eddy current	5362	1525	2.965	4520
Other stray	10888	3096	1.226	3795
Total losses	27000	9109		12803

V. RESULTS AND ANALYSIS

For Case 1 as in Table II, the harmonic loss factor for eddy current loss and harmonic factor for other stray loss are calculated using eqn. 11 and eqn. 12. Hence,

$F_{HL} = 2.965$, $F_{HL\text{-}STR} = 1.226$

In this case, the transformer loading is considered 0.5 per unit. The total load loss of the transformer being used in eqn. (13) is,

$$P_{LL-pu} = 0.2843pu$$

The load losses are also calculated considering the actual load and the effects of harmonic. The total eddy current loss and other stray loss are also determined using harmonic loss factor for eddy current loss and harmonic factor for other stray losses. The breakdown of the losses is summarized in Table III.

The result shows that the harmonic load current can be detrimental on the power transformer, which is about 40.55% losses increased with harmonic present. With 0.5 per unit loading, the aging acceleration factor is less than 1. This means that the transformer life will not be less than its normal life. However, with the same harmonic levels, 30°C ambient temperature and references temperature of 110°C, if the load is increased to 0.81 per unit, the aging acceleration factor will be 1.72 and the real life of this transformer decreased from 20.55 to about 11.95 years as shown in Fig. 2. Fig.2 also shows that for the total harmonic distortion 37.05% the transformer will have a normal life with loading smaller than 0.78 per unit, because its aging factor is less than 1.

For Case 2, from the simulation result, Fig.3 shows that the transformer still has its normal life for the higher load but if the load exceeds 98%, the transformer's real life will decrease dramatically.

When the harmonic limit are applied for both cases, Fig.4 and Fig.5 show the curve of transformer's real life reduction versus per unit loading, for Case 1 the

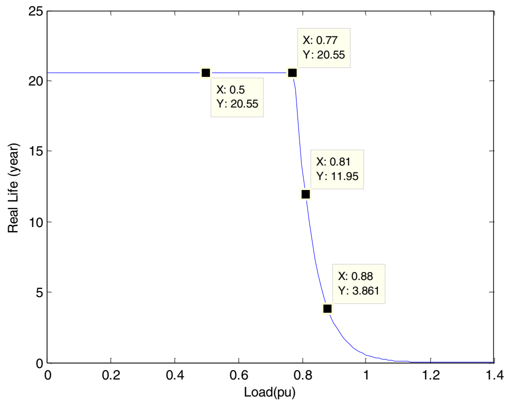

Figure 2: Transformer life versus loading

(Case I-THD 37.05%)

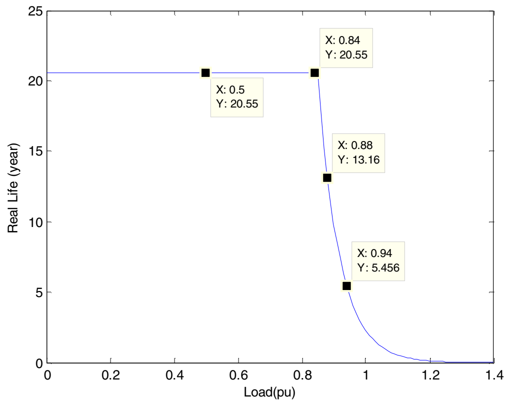

Figure 4: Transformer life versus loading

(Case I- Max Limit)

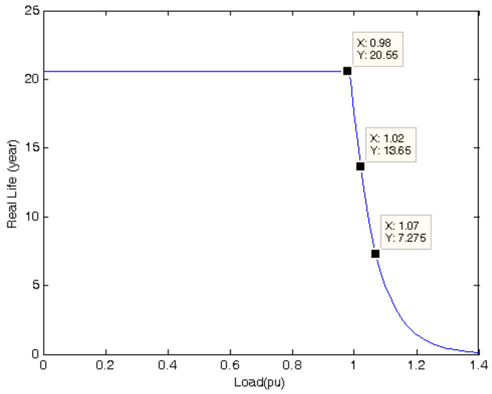

Figure 3: Transformer life versus loading

(Case II-THD 18.36%)

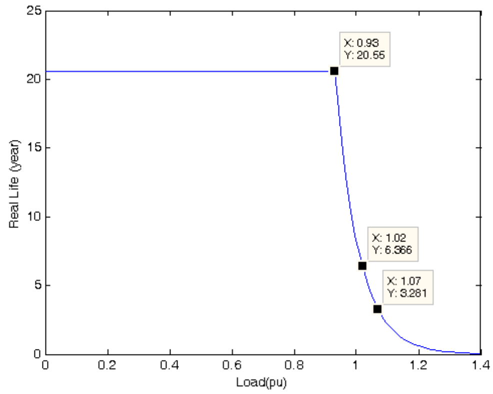

Figure 5: Transformer life versus loading

(Case II-Max Limit)

limit of per unit load to maintain its normal life increased from 0.77 per unit to 0.84 per unit. However the maximum limit was decreased in Case 2 because of the measured harmonic data are lower than the maximum limit.

VI. CONCLUSION

The simulation result of harmonic effect on transformer shows that higher the loads, the lower will be the life of transformer due to current harmonics generated by the electrical devices. Higher THD also lower the life of transformer, due to the increase of transformer losses and hot spot temperature.

In Case I, the transformer will not be less than its normal life until the loading exceed 0.77 per unit. For Case 2, the transformer will maintain its real life until the loading is 0.98, it is sufficient to apply the standard only in Case I. The harmonic standard shows that harmonic current need to be monitored. These maximum limits of MS 1555:2002 [15] which correspond to IEC TR 61000-3-4:1998 Standard should be used as a guide for both customer and suppliers facing the highest total harmonic distortion to protect the power system equipment that could be affected by high harmonic currents and raise the quality of power supply.

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