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Evaluation of Distribution Transformer Losses Under Harmonic Loads Using Analytical and Simulation Methods

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ABSTRACT : Transformers are normally designed and built for use at rated frequency and perfect sinusoidal load current. A non-linear load on a transformer leads to harmonic power losses which cause increased operational costs and additional heating in power system components. It leads to higher losses, early fatigue of insulation, premature failure and reduction of the useful life of the transformer. To prevent these problems, the rated capacity of transformer which supplies harmonic loads must be reduced. In this work a typical 100 KVA three phase distribution transformer with real practical parameters is taken under non-linear loads generated due to domestic loads. The equivalent losses and capacity of the distribution transformer is evaluated using the conventional method & also by using soft computing technique using MATLAB simulation based on valid model of transformer under harmonic conditions.

And finally a relation associated with transformer losses and life assessments are reviewed & analyzed and then a comparison is being carried out on the results obtained by both the methods.

Keywords: Transformer losses; Harmonic loads; Derating.

I. INTRODUCTION

In recent years, there has been an increased concern about the effects of nonlinear loads on the electric power system. Nonlinear loads are any loads which draw current which is not sinusoidal and include such equipment as fluorescent lamp, gas discharge lighting, solid state motor drives, battery chargers, UPS systems, and the increasingly common electronic power supply. While nonlinear loads are not new, their increased use means a larger percentage of any power system tends to be nonlinear. Additionally, nonlinear loads were once thought to be a concern only to industrial power systems where large static power converters are used. Such is not the case today. With the widespread application of electronics to virtually every electrical load, nonlinear loads are also prevalent in commercial and even residential power systems.

Nonlinear loads generate harmonic currents which flow from the load towards the power source, following the paths of least impedance. Harmonic currents are currents which have frequencies that are whole number multiples of the fundamental (power supply) frequency. The harmonic currents superimposed on the fundamental current result in the non-sinusoidal current waveforms associated with nonlinear loads.

Harmonic currents adversely affect virtually every component in the power system, creating additional dielectric, thermal, and/or mechanical stresses. The harmonic currents flowing through the power system impedances result in harmonic voltage drops which are observed as harmonic voltage distortion.

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 power quality problems have been identified and recognized as early in 1990 but the progress in managing the problems nationally has been quite slow. Harmonics proliferation in power distribution system with the increasing use of nonlinear loads [1], have become the power quality problem for both customers and suppliers. 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.

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 [2]. 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. 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 [3]. Therefore the influence of the current harmonics is more important. A lot of works have been done to show that effect of harmonic effect of harmonics on loss of life of distribution transformer. However, these works did not taken into account the standard of harmonics for residential loads given by IEEE 57.110 standards [1]. In this study harmonic current due to various non-linear residential loads are measured and the loss of life of distribution transformer is calculated, this study looks at the transformer loss of life when the international standards on harmonics limit are referred.

II. TRANSFORMER LOSSES IN HARMONIC LOADS

Transformer manufacturers usually try to design transformers [2] in a way that their minimum losses occur in rated voltage, rated frequency and sinusoidal current. However, by increasing the number of non-linear loads in recent years, the load current is no longer sinusoidal. This non-sinusoidal current causes extra loss and temperature in transformer.

Transformer loss is divided into two major groups, no load and load loss [4, 6]:

$$P_T = P_{NL} + P_{LL} \qquad \text{... (1)}$$

where P_{NL} is no load loss, P_{LL} is load loss, and P_T is total loss.

A brief description of transformer losses and harmonic effects on them is presented in following:

A. No Load Loss: No load loss or core loss appears because of time variable nature of electromagnetic flux passing through the core and its arrangement is affected the amount of this loss. Since distribution transformers are always under service, considering the number of this type of transformer in network, the amount of no load loss is high but constant this type of loss is caused by hysteresis phenomenon and eddy currents into the core. These losses are proportional to frequency and maximum flux density of the core and are separated from load currents [4].

Many experiments have shown that core temperature increase is not a limiting parameter in determination of transformers permissible current in the non-sinusoidal currents. Furthermore, considering that the value of voltage harmonic component is less than 5%, only the main component of the voltage is considered to calculate no load loss, the error of ignoring the harmonic component is negligible. So, IEEE C57 .110 standards has not considered the core loss increase due to non-linear loads and has supposed this loss constant, under non-sinusoidal currents.

B. Load loss: Load loss includes dc or Ohmic loss, eddy loss in windings and other stray loss and it can be obtained from short circuit test [5]:

$$P_{LL} = P_{DC} + P_{EC} + P_{OSL} \qquad \text{... (2)}$$

Here,

P_{DC} is loss due to resistance of windings, P_{EC} is windings eddy current loss, P_{OSL} is other stray losses in structural parts of transformer such as tank, clamps.

The sum of P_{EC} and P_{OSL} is called total stray loss. According to (3), we can calculate its value from the difference of load loss and Ohmic loss:

$$P_{TSL} = P_{EC} + P_{OSL} = P_{LL} - P_{DC} \qquad \text{... (3)}$$

It should be mentioned that there is no practical or experimental process to separate windings eddy loss and other stray loss yet.

(*i*) *Ohmic Loss:*

This loss can be calculated by measuring winding dc resistance and load current in (4):

$$P_{dc} = R_{dc} \times I^2 = R_{dc} \times \sum_{h=1}^{h=h_{max}} I^2{}_{h,\max} \qquad \text{... (4)}$$

(*ii*) *Eddy Current Loss in Windings:*

This loss is caused by time variable electromagnetic flux that covers windings. Skin effect and proximity effect are the most important phenomenon in creating these losses. In transformers, in comparison to external windings, internal windings adjacent to core have more eddy current loss. The reason is the high electromagnetic flux intensity near the core that covers these windings.

Also, the most amount of loss is in the last layer of conductors in winding, which is due to high radial flux density in this region [2]:

$$P_{EC} = \frac{\pi\tau^2\mu^2}{3\rho} f^2 \times H^2 \alpha f^2 \times I^2 \qquad \text{... (5)}$$

Here:

τ = A conductor width perpendicular to field line.

ρ = Conductor's resistance.

$$P_{EC} \propto I^2 f^2 \qquad \text{... (6)}$$

Equation shown below can be used for calculating the eddy current loss too:

$$P_{EC} = \mathrm{P}_{\mathrm{LL-R}} - [(R_1 I^2{}_{1-R} - R_2 I^2{}_{2-R})] \qquad \text{... (7)}$$

According to IEEE C57 .110 standards, the amount of rated eddy current loss of windings is about 33% of total stray loss for oil-filled transformers:

$$P_{EC-R} = 0.33 P_{TSL} \qquad \text{... (8)}$$

C. Other stray loss: Due to the linkage between electromagnetic flux and conductor, a voltage induces in the conductor and this will lead to producing eddy current Eddy current produces loss and increases temperature. A part of eddy current loss which is produced in structural parts of transformers (except in the windings) is called other stray loss [2, 6]. Many factors such as size of core, class of voltage of transformer and construction of materials used to build tank and clamps. To determine the effect of frequency on the value of other stray loss, different tests have been fulfilled. Considering the results derived from

[5], the resistance of other stray loss in low frequency (0-360Hz) is equal to

$$R_{AC}^{if} = 0.00129\left(\frac{f_h}{f_1}\right)^{0.8} \quad \text{... (9)}$$

The frequencies in the range of (420-1200 Hz), resistance will be calculated by:

$$R_{AC}^{hf} = 0.33358\left(\frac{f_h}{f_1}\right)^{-1.87} \quad \text{... (10)}$$

Thus this loss is proportional to the square of the load current and the frequency to the power of 0.8

$$P_{EC} \propto I^2 \propto f^{0.8} \quad \text{... (11)}$$

Below equation can be used for calculating the other stray loss

$$P_{OSL} = P_{TSL} - P_{EC} \quad \text{... (12)}$$

III. EFFECT OF HARMONICS ON NO-LOAD LOSSES

According to Faraday's law the terminal voltage determines the transformer flux level, i.e.:

$$N^d\,(I^{dt}) = v(t) \quad \text{... (13)}$$

Transferring this equation into the frequency domain shows the relation between the voltage harmonics and the flux components:

$$Nj(h\omega) = V_h \quad \text{... (14)}$$

The effects of voltage harmonics and the no load losses caused by the fundamental voltage component, (14) shows that the flux magnitude is proportional to the voltage harmonic and inversely proportional to the harmonic order h. Furthermore, within most power systems, the harmonic distortion of the system voltage THD is well below 5% and the component, rarely exceeding a level of 2-3%. Therefore, neglecting will only give rise to an insignificant error. This is confirmed by measurements in [3]. Nevertheless, if THDv is not negligible, losses under distorted voltages can be calculated based on ANSI-C.27-1920 standard with (14).

$$P = P_M\left[P_h + P_{ec}\left(\frac{V_{hrms}}{V_{rms}}\right)^2\right] \quad \text{... (15)}$$

where,

V_{hrms} and V_{rms} are the RMS values of distorted and sinusoidal voltages, P_M and P are no-load losses under distorted and sinusoidal voltages, P_h and P_{EC} are hysteresis and eddy current losses, respectively [4].

IV. EFFECT OF HARMONICS ON LOAD LOSSES

As per [1], in most power systems, current harmonics are of more significance. These harmonic current components cause additional losses in the windings and other structural parts.

A. Effect of Harmonics on DC Losses:

If the rms value of the load current is increased due to harmonic components, then these losses will increase by square of RMS of load current [4]. The windings Ohmic loss under harmonic condition is shown by:

$$P_{dc} = R_{dc} \times I^2 = R_{dc} \times \sum_{h=1}^{h=h_{\max}} I_{h,\max}{}^2 \quad \text{... (16)}$$

B. Effect of Harmonics on Eddy Current Losses:

As mentioned above, eddy current loss of windings is proportional to square of current and square of harmonic frequency in harmonic condition. In following equation, this loss is calculated [5, 6]:

$$P_{EC} = P_{EC-R} \times \sum_{h=1}^{h=h_{\max}} h^2\left[\frac{I_h}{I_R}\right]^2 \quad \text{... (17)}$$

where,

P_{EC-R} is Rated eddy current loss of windings, I_h is the current related hth harmonics I_R is Rated load current, h is the Order of harmonics. Also, the harmonic loss factor for eddy current loss of winding can be defined according to [5, 8]:

$$P_{HL} = \frac{\sum_{h=1}^{h=h_{\max}} h^2 I_h{}^2}{\sum_{h=1}^{h=h_{\max}} I_h{}^2} = \frac{\sum_{h=1}^{h=h_{\max}} h^2\left[\frac{I_h}{I_R}\right]^2}{\sum_{h=1}^{h=h_{\max}}\left[\frac{I_h}{I_R}\right]^2} \quad \text{... (18)}$$

C. Effects of Harmonics on Other Stray Losses:

The other stray losses are assumed to vary with the square of the rms current and the harmonic frequency to the power of 0.8:

$$P_{OSL} = P_{OSL-R}\, X \sum_{h=1}^{h=h_{\max}} h^{0.8}\left[\frac{I_h}{I_R}\right]^2 \quad \text{... (19)}$$

Harmonic loss factor for other stray losses is expressed in a similar form as for the winding eddy currents [6].

$$F_{HL-STR} = \frac{P_{OSL}}{P_{OSL-R}} = \frac{\sum_{h=1}^{h=h_{\max}} h^{0.8}\left[\frac{I_h}{I_R}\right]^2}{\sum_{h=1}^{h=h_{(\max)}}\left[\frac{I_h}{I_R}\right]^2} \quad \text{... (20)}$$

So under non-sinusoidal currents it is only necessary to multiply the rated other stray loss by harmonic loss factor, F_{HL-STR}.

V. EVALUATION OF LOSSES AND CAPACITY OF TRANSFORMER IN HARMONIC LOADS

When a transformer is utilized under non-sinusoidal voltages and currents, due to loss increase results, increase of temperature, and its rated power must decrease [8]. This action will be possible by limiting total transformer loss under non-sinusoidal current to the amount of loss in sinusoidal voltage and load current. In other word, maximum permissible current of transformer in harmonic load must be determined as its loss would be equal to the loss in hot spot and under sinusoidal current condition. The equation that applies to linear load conditions is [7]:

$$P_{LL-R}(Pu) = 1 + P_{EC-R}(Pu) + P_{OSL-R}(Pu) \quad \text{... (21)}$$

where, P_{LL-R} is Rated load losses, I is per unit amount of dc losses, P_{EC-R} is Eddy current loss, P_{OSL-R} is Other Stray loss in rated current.

As the effect of harmonic on losses of transformer evaluated in previous sections, a general equation for calculating of losses when transformer supplying a harmonic load can be defined as follows [7]:

$$P_{LL-R}(Pu) = I^2(Pu) \times [1 + F_{HL} P_{EC-R}(Pu) + F_{HL-STR} P_{OSL-R}(Pu)] \quad \text{... (22)}$$

So, maximum permissible load current to determine the capacity reduction of transformer is expressed as [9]:

$$I_{\max}(Pu) = \sqrt{\frac{P_{LL-R}(Pu)}{1 + [F_{HL} P_{EC-R}(Pu)] + [F_{HL-STR} P_{OSL-R}(Pu)]}} \quad (23)$$

Based on this equation, we can determine the maximum permissible load current of transformer and also, determine its capacity reduction under non-sinusoidal current of transformer called "Derating" [7, 9].

VI. CALCULATION OF LOSSES AND CAPACITY OF TRANSFORMER UNDER HARMONIC LOADS

In this section calculation and simulation of losses and capacity of transformer under harmonic loads is performed. As stated earlier various commonly domestic loads are been considered like CFL, Laptop, Computer, E.T.L., Mobile Charger and U.P.S. etc. These loads are been analyzed using power analyzer (HIOKI 3193) and the harmonic parameters are shown in Table 1.

The distortion in waveforms deteriorates the performance of equipment connected in distribution system. The analysis of the harmonics is essential to determine the performance and designing of equipments. Table 1 shows the analysis of some leading equipments under harmonics in terms of Current Distortion, Total Power Factor (T.P.F.), Extra Units Consumed etc.

Table 1: Analysis of some non-linear loads

Equipments	V_{rms}	I_{rms}	*TPF*	*Extra Unit Consumed*	*Current Distortion*
C.F.L.	214.81	0.106	0.56	0.019	126.5%
Laptop	216.82	0.261	0.41	0.059	204%
Computer	234.32	0.631	0.55	0.075	138.6%
E.T.L.	213.93	0.145	0.64	0.035	91%
Mobile Charger	213.36	0.027	0.54	0.006	144.7%
U.P.S.	213.94	0.113	0.70	0.021	51.68%

A. Analytical Method

The generic parameters of a 100 KVA three phase distribution transformer that designed with specifications are summarized in Table 2. The total stray loss PTSL can be calculated as follows:

$$P_{TSL} = P_L - P_{DC} = 1760 - 3[I_1^2R_1 - I_2^2R_2] = 110 \text{ W}$$

The winding eddy current loss and other stray loss are

$$P_{EC} = 0.33[110] = 36.3 \text{ W}$$

$$P_{OSL} = 110 - 36.3 = 73.7 \text{ W}$$

Table 2: Transformer parameter.

V_1(V)	V_2(V)	I_1(A)	I_2(A)	P_O(W)	P_{SC}(W)
11000	433	5.25	133.3	260	1760

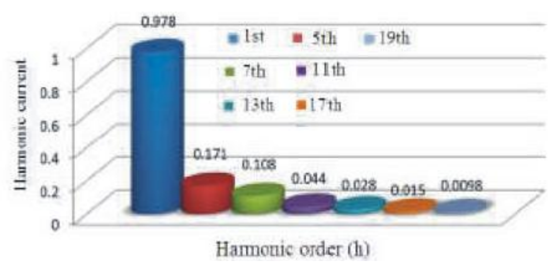

Fig. 1. Non-linear Load Specification for Studied Transformer.

If transformer supplying a load with specification in Table 3 losses on harmonic load calculated as follows:

Table 3: Harmonic load specification.

1	5	7	11	13	17	19
0.978	0.171	0.108	0.044	0.028	0.015	0.009

The harmonic loss factor for eddy current winding and other stray losses are: FHL = 3.734, FHL-STR = 1.202

Table 4 shows losses under harmonic load. Total loses increases about 23.1% under harmonic condition load. These increase in total losses results from significant increase in eddy current losses in winding.

Table 4: Losses under Harmonic load.

Types losses	*Rated losses (W)*	*Losses under harmonic load current (W)*	*Harmonic losses factor*	*Corrected losses under harmonic load (W)*
No-load	260	260	—	260
Dc	1650	1985.23	—	1985.23
Winding eddy current	36.3	38.805	3.734	144.92
Other stray	73.3	78.79	1.202	94.67
Total	2020	2141.45	—	2486.6

In addition from (23), the rms value of the maximum permissible non-sinusoidal load current with the given harmonic component is:

$$I_{\max}(Pu) = \sqrt{\frac{1.119}{1.612}} = 0.8337$$

$$0.8337 \times 133.3 = 111.13 \text{ Amp}$$

Equivalent KVA = 100 × 0.8337 = 83.37 KVA.

B. Simulation method

Basically Transformers model consist of ordinary parameters such as the leakage inductances and dc resistances, magnetizing inductances and core resistance that can be obtained from no-load test, short circuit test and dc test. In this model, stray losses that consist of eddy current losses in windings and other stray losses do not considered [7]. When transformer supplies harmonic loads the losses that are proportional with frequency is more considerable. Figure 8 shows the proposed transformer model with the proximity effect loss represented as a potential difference defined as the second derivative of the load current and the other stray losses represented as a resistor in series with the leakage inductance and dc resistance [10].

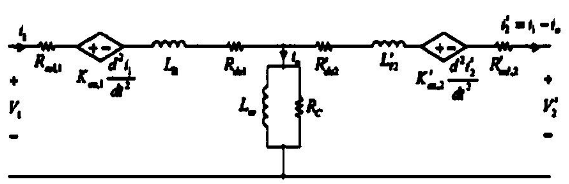

Fig. 2. Proposed Equivalent Transformer Model Referred to Primary Side.

The parameters required to simulate the transformer are summarized in Table 5.

Table 5: Losses under harmonic load by simulation.

Types losses	*Rated losses (w)*	*PLL lossed rms harmonic load current (w)*
No-load	262.54	262.54
dc	1647.76	1983.22
Winding eddy current	31.94	132.58
Other stray	74.24	92.81
Total	2016.48	2471.15

MATLAB/Simulink is used to simulate the obtained transformer model. Fig. 3 shows the in proposed model of transformer MATLAB/Simulink [10]. Current sources with different frequencies are put in parallel to model for harmonics in residential loads in Figure 9. The power losses are determined through simulations and summarized on Table 5. Thus, the rms value of the maximum permissible non-sinusoidal load current composition from equation (23) is with given harmonics [9]:

$$I_{\max}(Pu) = \sqrt{\frac{1.121}{1.573}} = 0.8441$$

$I_{\max}$ = 0.8441 × 133.3 = 112.52 Amp

Equivalent KVA = 100 × 0.8443 = 84.43 KVA

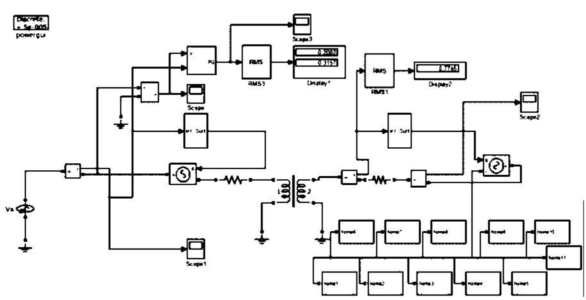

Fig. 3. Simulation Model for Transformer.

The comparison between two steps (Table 6) shows that the predicted values using analytical and simulation methods are similar but simulations shows smaller losses then the analytical method. The reason is that in the analytical method it is assumed that the eddy current losses are proportional with the square of harmonic orders that is a permissible assumption.

Table 6: Comparison between analytical and simulation method.

Conclusion	*Based on analytical method*	*Based on simulation method*
Losses under linear load (w)	2020	2016.48
Losses under harmonic load (w)	2484.6	2471.15
Percent of increase losses	23.01%	22.54%
Capacity under harmonic load (KVA)	83.37	84.43
Percent of decrease capacity	16.63%	15.57%

VII. CONCLUSION

In this paper, impacts of harmonic components on transformers have been reviewed and analyzed. Effects of non-linear loads on transformer losses based on the conventional method (IEEE standard C57-110) have been studied for derating purpose. The harmonic losses factor for eddy current winding and other stray losses has been computed in order to evaluate the equivalent KVA of the transformer for supplying non-linear loads. A useful model of transformer was presented for calculating losses and capacity under harmonic condition. Then losses and capacity of a transformer were evaluated with analytical and simulation methods. The result shows that losses increase in harmonic load and therefore decrease the useful capacity and real life of transformers. Assumption of increase of the winding eddy current losses with the square of the frequency in the analytical methods and the available standards is somehow less accurate. So every changing in current harmonic leads to change in harmonic losses factor and thus cause to change losses and capacity of transformer. For power systems with transformer, it is better to carry out monitoring on voltage and current, to reach to useful capacity of transformer based on available standards and the proposed model, if harmonic components exist.

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