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The Performance Analysis of Distribution Transformer under Domestic Harmonics Load

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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 to 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 performed under non-sinusoidal loads generated due to domestic loads. The equivalent losses and capacity of the distribution transformer is evaluated using the conventional method.

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 like electronic loads. 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 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 [1].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 [2]. In this study harmonic current due to various non-linear residential loads are measured & the loss of life of distribution transformer is calculated under harmonic loads.

II. TRANSFORMER LOSSES UNDER NON-LINEAR 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. It results additional losses and temperature in transformer.

Transformer loss is divided into two major groups, no load and load loss [3, 4]:

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

Where P_{NL} is No load loss, P_{LL} is Load loss, and P_T is total loss.

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A brief description of various losses on distribution transformer and harmonic effects on it is presented in following:

A. No Load Loss: Since distribution transformers are always under services so the amount of no load loss is not 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 [5].

B. Load Loss: Load loss contains Ohmic losses, eddy loss in windings and other stray loss and it can be obtained from short circuit test [6]:

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

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:

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

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):

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

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.
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 [4]:

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

Here:
τ = A conductor width perpendicular to field line.
ρ = Conductor's resistance.

$$P_{EC} \propto I^2 \times f^2 \quad (6)$$

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

$$P_{EC} = P_{LL\text{-}R} - [(R_1 I_{1\text{-}R}^2 - R_2 I_{2\text{-}R}^2)] \quad (7)$$

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:

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

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].

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

$$P_{EC} \propto I^2 \propto f^{0.8} \quad (9)$$

Below equation can be used for calculating the other stray loss

$$P_{OSL} = P_{TSL} - P_{EC} \quad (10)$$

III. EFFECT OF HARMONICS ON NO-LOAD LOSSES

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

$$N\frac{d\Phi}{dt} = v(t) \quad (11)$$

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

$$Nj(h\omega) = V_h \quad (12)$$

The effects of voltage harmonics and the no load losses caused by the fundamental voltage component, 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 [3]. Nevertheless, if THDv is not negligible, losses under distorted voltages can be calculated based on ANSI-C.27-1920 standard with (14).

$$P = P_M [P_h + P_{ec} (\frac{V_{hrms}}{V_{rms}})^2] \quad (13)$$

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].

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IV. IMPACTS OF HARMONICS ON LOAD LOSSES CALCULATION

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:

$$P_{dc} = R_{dc} \times I^2 = R_{dc} \times \sum_{h=1}^{h=h_{max}} I^2_{h,max} \qquad (14)$$

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]:

$$P_{EC} = P_{EC-R} \times \sum_{h=1}^{h=h_{max}} h^2 [\frac{I_h}{I_R}]^2 \qquad (15)$$

Where, PEC-R is Rated eddy current loss of windings, Ih is the current related hth harmonics IR 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]:

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} h^2 I_h{}^2}{\sum_{h=1}^{h=h_{max}} I_h{}^2} = \frac{\sum_{h=1}^{h=h_{max}} h^2 [\frac{I_h}{I_R}]^2}{\sum_{h=1}^{h=h_{max}} [\frac{I_h}{I_R}]^2} \qquad (16)$$

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:

$$P_{OSL} = P_{OSL-R} X \sum_{h=1}^{h=h_{max}} h^{0.8} [\frac{I_h}{I_R}]^2 \qquad (17)$$

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

$$F_{HL-STR} = \frac{P_{OSL}}{P_{OSL-R}} = \frac{\sum_{h=1}^{h=h(\max)} h^{0.8} [\frac{I_h}{I_R}]^2}{\sum_{h=1}^{h=h(\max)} [\frac{I_h}{I_R}]^2} \qquad (20)$$

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

V. EVALUATION OF LOSSES AND CAPACITY OF TRNSFORMER 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 [7]. The 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 [6]:

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

Where, P_{LL-R} is Rated load losses, 1 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 generalized equation for calculating of losses under harmonic loads can be defined as follows [7]:

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

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

$$I_{max}(pu) = \sqrt{\frac{P_{LL-R}(pu)}{1 + [F_{HL}.P_{EC-R}(pu)] + [F_{HL-STR.}P_{OSL-R}(pu)]}} \qquad (20)$$

VI. EFFECTS OF HARMONICS ON DOMESTIC LOADS

In this section, we are analyzing the impacts of harmonics on some of the standard domestic loads. These loads are been analyzed using power analyzer (HIOKI 3193) and the current waveforms are shown below in Figure 1 to 6. Some of the commonly domestic loads are observed like CFL, Laptop, Computer, E.T.L., Mobile Charger & U.P.S. etc.

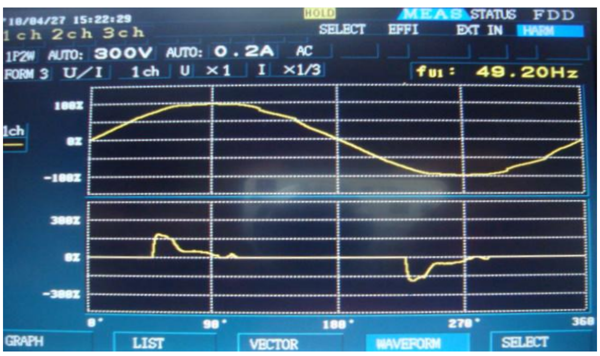

Figure 1: waveform for C.F.L.

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Figure 2: waveform for Laptop

Figure 5: waveform for Mobile Charger

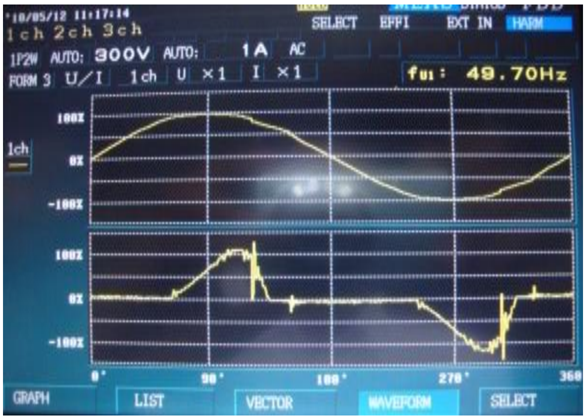

Figure 3: waveform for Computer

Figure 6: waveform for U.P.S.

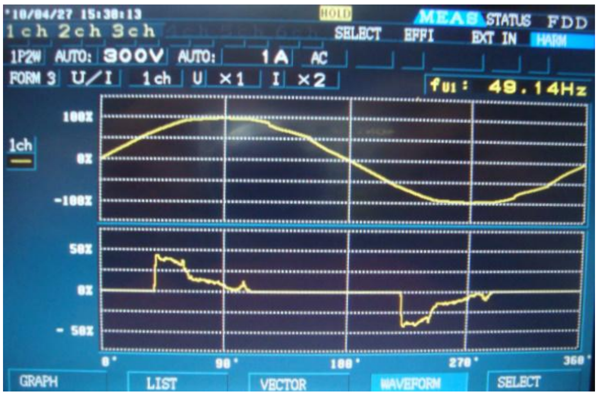

Figure 4: waveform for E.T.L.

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.

A. Calculation for Transformer Derating under Harmonic Loads:

The generic parameters of a 100 KVA three phase distribution transformer that designed with specifications are summarized in Table 2.The total stray loss P_{TSL} can be calculated as follows[10]:

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

The winding eddy current loss and other stray loss are

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

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

TABLE 1: ANALYSIS OF SOME NON-LINEAR EQUIPMENT

Equipments	V_{rms}	I_{rms}	TPF	Extra Units 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%

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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

The calculations of losses and capacity of transformer under harmonic loads is performed below 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.

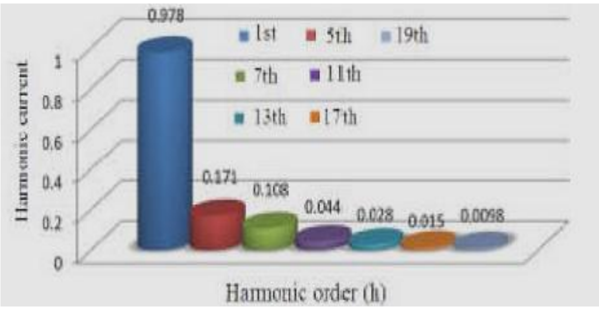

Figure 7:Non-linear Load Specification for Studied Transformer.

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: F_{HL} = 3.734, $F_{HL\text{-}STR}$ = 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 [10].

TABLE 4: LOSSES UNDER HARMONIC LOAD

Types of 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, 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× 133.3 = 111.13 Amp

Equivalent KVA = 100 ×0.8337 = 83.37 KVA

VI. 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 purposes. 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 methods. The result shows that losses increase in harmonic load and therefore decrease the useful capacity and real life of transformers.

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