EFFECT OF TYPES OF LOADS IN RATING OF TRANSFORMERS SUPPLYING HARMONIC-RICH LOADS

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ABSTRACT

Nonlinear loads cause harmonics to flow in the power lines which can overload wiring and transformers. Many desktop, personal computers present nonlinear loads to the AC supply because of their power supplies design (capacitor input power supply).

In power transformers the main consequence of harmonic currents is an increase in losses, mainly in windings, because of the deformation of the leakage fields. Higher losses mean that more heat is generated in the transformer so that the operating temperature increases, leading to deterioration of the insulation and a potential reduction in lifetime. As a result, it is necessary to reduce the maximum power load on the transformer, a practice referred to as de-rating, or to take extra care in the design of the transformer to reduce these losses. To estimate the de-rating of the transformer, the load's K-factor may be used.

So, in this paper a proposed methodology has been introduced to calculate this factor according to the harmonic spectrum of the load current and is an indication of the additional eddy current load losses. It reflects the excess losses experienced in a traditional wire wound transformer. Also an analysis has been conducted relating transformer efficiency to its load; as well as concluding an energy saving.

This method has been applied on a 500 kva transformer.

INTRODUCTION

Events over the last several years have focused attention on certain types of loads on the electrical system that result in power quality problems for the user and utility alike. Equipment which has become common place in most facilities including computer power supplies, solid state lighting ballasts, adjustable speed drives (ASDs), and uninterruptible power supplies (UPSs) are examples of non-linear loads. It is forecast that before the end of the century, half of all electrical devices will operate with nonlinear current draw. These nonlinear loads are the cause of current harmonics [1].

Non-linear loads are loads in which the current waveform does not have a linear relationship with the voltage waveform. Non-linear loads generate voltage and current harmonics which can have adverse effects on equipment that are used to deliver electrical energy such as transformers, feeders, circuit breakers, which are subjected to higher heating losses due to harmonic currents consumed by non-linear loads.

The current waveform at the input of such equipment is not continuous It has multiple zero crossings in one electrical cycle as shown in Figure 3. The discontinuous, Harmonic currents cause overheating of electrical distribution system wiring, transformer overheating and shortened transformer service life. Electrical fires resulting from distribution system wiring and transformer overheating were rare occurrences until harmonic currents became a problem. Transformers which provide power into an industrial environment are subject to higher heating losses due to harmonic generating sources (non-linear loads) to which they are connected.

The major source of harmonic currents is the switch mode power supply found in most desktop computers, terminals, data processors and other office equipment is a good example of a non-linear load. The switching action of the computer power supply results in distortion of the current waveform [2]. Harmonics are produced by the diode-capacitor input section of power supplies. The diode-capacitor section rectifies the AC input power into the DC voltage used by the internal circuits. The personal computer uses DC voltage internally to power the various circuits and boards that make up the computer. The circuit of the power supply only draws current from the AC line during the peaks of the voltage waveform, thereby charging a capacitor to the Peak of the line voltage. The DC equipment requirements are fed from this capacitor and, as a result, the current waveform becomes distorted.

The increasing usage of non-linear loads on electrical power systems is causing greater concern for the possible loss of transformer life. So, Manufacturers of distribution transformers have developed a rating system called K-Factor, a design which is capable of withstanding the effects of harmonic load currents. The amount of harmonics produced by a given load is represented by the term "K" factor. The larger the "K" factor, the more harmonics are present[3]. From previous studies on losses, 10% of the losses occur in the 10kV high voltage cable, 60% occur in 10/0.4 kV distribution transformer and 30% in 400V low voltage cable [3].

So, this paper is aimed at investigating the concept of K-factor and the relationship between K-factor, de-rating, and the winding eddy-current loss of harmonic currents for transformer capacity when supplying non-sinusoidal load currents, recognizes that harmonic rich load . and how much of this 60% losses are due to harmonics effects in distribution transformers and investigating how much can be saved by changing the oversized and high-loss distribution transformers. A theoretical understanding on harmonics distortion can be helpful in developing suitable analysis for identifying the harmonics content within the total transformer losses. The transformer in this study has a rating of 500kVA and is used to show how harmonics affect the load loss.

1. PROPOSED TECHNIQUE:

Transformer losses are categorized as no-load loss (excitation loss); load loss (impedance loss); and total loss (the sum of no-load loss and load loss). This can be expressed by :

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

Where: P_T :Total loss, watt

P_C : Core or No load loss, watt

P_{LL}: Load loss, watt

Load loss is subdivided into I^2R loss and "stray loss". Stray loss" can be defined as the loss due to stray electromagnetic flux in the winding, core, core clamps, magnetic shields, enclosure or tank walls, etc [3].

It is determined by subtracting the I^2R loss (calculated from the measured resistance) from the measured load loss (impedance loss).

$$P_{LL} = I^2R + \text{stray loss}$$

$$\text{Or, stray loss} = P_{LL} - I^2R \tag{2}$$

"Thus, the stray loss is subdivided into winding stray loss and stray loss in components other than the windings (P_{OSL}). The winding stray loss includes winding conductor P_{EC} eddy-current loss and loss due to circulating currents between strands or parallel winding circuits. All of this loss may be considered to constitute winding eddy-current loss, P_{EC}. The total load loss can then be stated by :

$$P_{LL} = I^2R + P_{EC} + P_{OSL} \quad \text{watt} \tag{3}$$

eddy current loss (P_{EC}) in the power frequency spectrum tends to be proportional to the square of the load current and the square of frequency. It is this characteristic that can cause excessive winding loss and hence abnormal winding temperature rise in transformers supplying load currents. It is recognized that other stray loss (P_{OSL}) in the core, clamps, and structural parts will also increase at a rate proportional to the square of the load current.

However, these losses will not increase at a rate proportional to the square of the frequency, as in winding eddy losses. Studies at manufacturers and other researchers have shown that the eddy current loss in bus bars, connecting and structural parts increase by a harmonic exponent factor of 0.8 or less [4].

1.1 Effect of harmonics on load losses

In most power systems, current harmonics are of significance. Higher frequency components in the load current cause losses because harmonics do not fully penetrate the conductor. They travel on the outer edge of the conductor;, the effective cross sectional area of the conductor decreases; increasing the resistance and the I^2R losses. This in turn heats up the conductors slightly extra as well as objects in their vicinity. The I^2R losses are affected by harmonics if the rms value of the load current increases due to the harmonic components; then these losses will increase with square of the current [5].

Harmonic currents increase also the eddy current losses in transformers; these increase approximately with the square of the frequency. For linear loads eddy currents are a fairly small component of the overall load losses (approx. 5%). With non-linear loads however, they become a more significant component, sometimes increasing as much as by 15x to 20x. With the eddy current losses known, the eddy current losses due to any non-sinusoidal load current can be calculated as [6].

$$P_{EC} = P_{EC-R} \sum_{h=1}^{h_{\max}} h^2 \left(\frac{I_h}{I_R} \right)^2 \tag{3}$$

Where, P_{EC} = winding eddy current

P_{EC-R} = Winding eddy-current loss under rated conditions (per unit of rated load I^2R loss)

I_h = rms sine wave current under rated frequency and load conditions (amperes)

h = Harmonic order

1-2 determination of K-factor for transformer capacity with nonlinear loads.

The K factor describes the increase in eddy current losses, not total losses. if the current in a transformer winding is 100 A, and this current has a K-factor of 10, then the eddy current losses in that winding will be approximately 10 times what they would be for a 100 A sinusoidal current at the rated line frequency.

$$K = \sum_{h=1}^{h = h_{\max}} I_h^2 h^2 \tag{4}$$

Load losses harmonics are calculated according to equation (3) to show the losses when loaded with lr. The eddy current losses are assumed to be 10% of the total and the copper losses assumed to be 90% [7].

$$P_{LL} = P_{LL-R} * l_r^2 [0.9 + .1 * k\,) \tag{5}$$

1-3 Estimation of factor K

$$K = \left(1 + \frac{e}{1+e} \left(\frac{I_1}{I} \right)^2 \sum_{h=2}^{h_{\max}} \left(h^q \left(\frac{I_h}{I_1} \right)^2 \right) \right)^{\frac{1}{2}} \tag{6}$$

e : is ratio of eddy current loss (50 Hz) to resistive loss

h : is the harmonic order

q : is dependent on winding type & frequency

1-4 Distribution transformer efficiency

Distribution transformer efficiency is steadily improved with losses of less than 0.2% in large units. Most distribution transformers convert at least 98% of input power into usable output power. However, when the overall losses of the many transformation steps in a distribution system are considered, these losses can add up. Total transformer losses in percents of kVA load will be minimum when the no-load losses are equal to the load losses . The maximum efficiency is obtained with a loading of 40-70% of the rated apparent power [8].

$$\eta = \frac{l_r * KVA * pf \ * 1000}{l_r * KVA * pf \ * 1000 + NLL + LL * l_r^2} \tag{7}$$

1.5 Total cost of the distribution transformer losses

to calculate the losses of distribution transformers. Total Cost of Losses (TCL) is the methods used in determining the cost of transformer losses over its life [9] .

$$TCL_{loss} = E_{loss} * C_e * \frac{(1+r^n)-1}{r*(1+r)^n} \quad (8)$$

where: r= the cost of capital

n= the life time of the transformer in years.

C_e = average cost per kWh (LE/kWh)

$$E_{loss} = (p_{NLL} + P_{LL} * (l_r)^2) * 8760 \quad (9)$$

Where: P_{NLL} = is the no-load loss in kW

P_{LL} = is the load loss in kW

2. APPLICATION

The transformer in the case study has a rating of 500kVA and it shows how harmonics affect the load loss. Figure 1 shows the line diagram of Typical 500 kVA loss profile which concluded that the total power loss of transformers with linear loads. Figure 2 shows the full-load losses for this transformer which illustrates that The eddy current losses are assumed to be 10% of the total and the copper losses assumed to be 90%, figure 3 shows shows the Current waveform for a typical Personal Computer Harmonic. Also, figure 4 describes a profile of a typical Personal Computer which illustrate in particular the high levels of third and fifth harmonics there was also the seventh, ninth and eleventh harmonic.

These data used to calculate the of k factor and the factor k for derating the transformer and given in table 1 and table 2. The impact of this harmonic on transformer losses developed and illustrated in Figure 5 and 6. Figure 5 shows Transformer losses under nonlinear loads. The overall efficiency of the transformer can be affected by high levels of harmonic distortion; the maximum efficiency is obtained with a loading of 40-70% of the rated apparent power. Figure 7 compares the efficiencies of transformer affected by linear and non-linear loading. Then, figure 8 depict the total cost of transformer losses supplying harmonic rich loads.

Table 1. calculation of k factor

H	Ih	Ih2	h2	k factor
1	1	1	1	1
3	0.8	0.64	9	5.76
5	0.15	0.0225	25	0.5625
7	0.1	0.01	49	0.49
9	0.18	0.0324	81	2.6244
11	0.08	0.0064	121	0.7744
				11.6

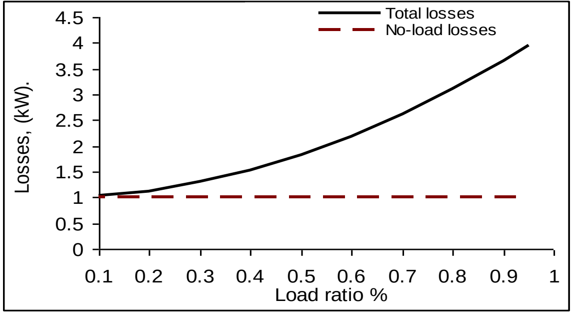

Figure 1. Typical 500 kVA loss profile with linear loads

Table 2. calculation of factor k

h^q	(Ih/I1)2 x hq	a	[a] x (Ih/I)2		e/(e+1)	k
1.0	1.0	12.5	3.2	2.1	0.1	1.6
6.5	4.1	12.5	2.1	3.1		0.6
15.4	3.1	12.5	0.7	1.7		
27.3	2.5	12.5	0.3	1.3		
41.9	1.4	12.5	0.1	1.1		
58.9	0.4	12.5	0.0	1.0		
	0.0					
	12.5					

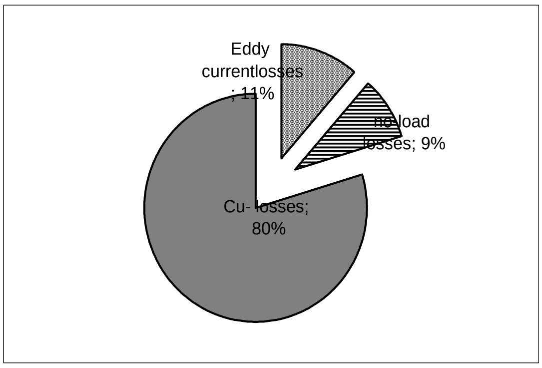

Figure 2. Total power loss of transformers with linear loads.

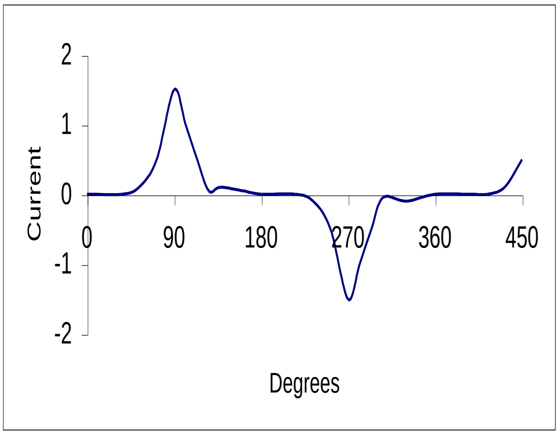

Figure 3. Current waveform for a typical Personal Computer.

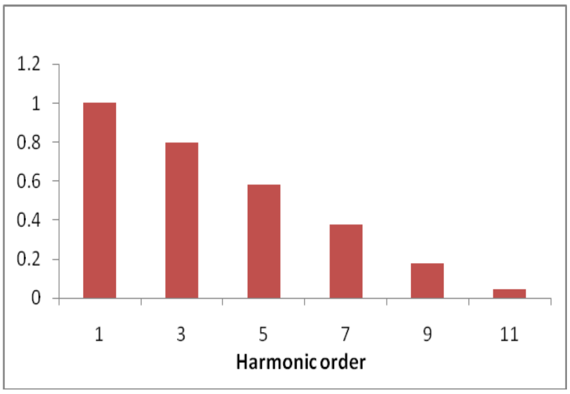

Figure 4. Profile of a typical Personal Computer

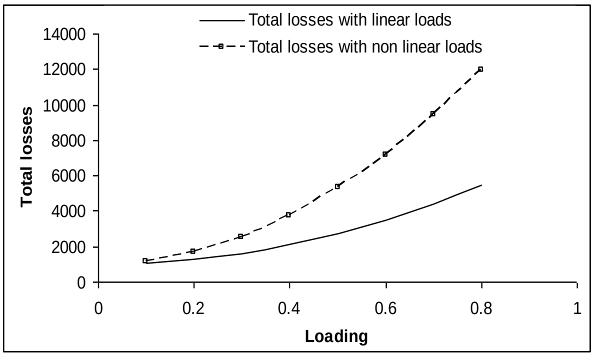

Fig 5. comparing between losses of transformer with and without non linear loads

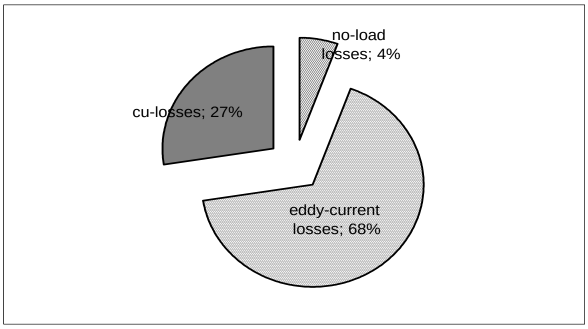

Fig 6. Full load losses in a 500kVA transformer

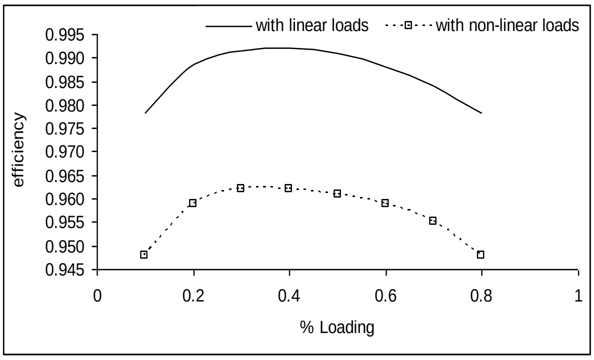

Fig 7. Transformer efficiency affected by linear and non-linear loading

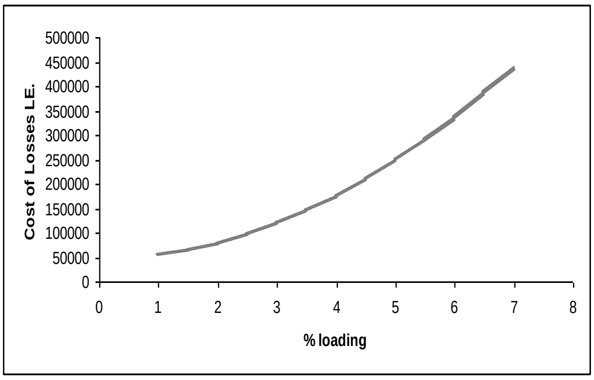

Fig. 8 the total cost of transformer losses

CONCLUSION

Non-sinusoidal currents cause excessive heating in transformers due to the increase in the losses, especially the eddy current losses. K-Factor transformers differ from standard transformers. The most common type of distribution transformer coupling for low voltage distribution 10/0.4 kV is the Delta-wye. Distribution transformers are designed to operate at frequencies of 50 Hz, but there are loads which also produce currents and voltages with frequency that are integer multiples of the 50 Hz fundamental frequency; this type of distortion effect on transformers leads to increased losses and heating as well as affecting the lifetime of the transformers.

Where existing or standard transformers are used to supply non-linear loads, they should be de-rated in a manner appropriate to their construction. The remarkable results of this application are:

1. the K-Factor for transformers supplys personal computer equal 11.6
2. Eddy current losses at the fundamental are normally around 10 % of the resistive losses, so that a load K factor of 11.6 would require de-rating to 60 %
3. the total losses for transformer with linear loads equal 5000 kw , while this losses become 12000 kw when supplying harmonic loads for 500 kVA transformer.
4. the efficiency of the transformer at loading from 0.4 to 0.7 equal 0.99 and reduced to 0.96 when supplying harmonic loads.
5. the cost of losses reaches to 440,000 at .7 loading ratio.
6. taking q as 1.7 and assuming that eddy current loss at fundamental is 10% of resistive loss i.e. e= 0.1). So, that a load K factor of 11.6 would require de-rating to 70 % load .

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