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Simulation of Proximity Effect in Transformer Due to Harmonic Loads

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Abstract

The AC loss in a transformer winding is mainly due to the sum of the I^2R losses produced by the fundamental and harmonic components of the current, recognizing that for each component, R depends on the frequency of that component. For lower-order harmonics, the frequency dependence of the winding resistance is primarily due to the proximity effect, a phenomenon that occurs in coils because the magnetic field surrounding each conductor in a coil depends on the fields produced by other conductors. The proximity effect produces greater losses than those predicted by the skin effect, which is dominant at higher frequencies. The proximity effect therefore accounts for the largest contribution to winding eddy currents under harmonic load current. The proximity effect in transformers which can be the most severe under harmonic conditions are estimated to be proportional to the square of frequency. Finally, the model simulated in MATLAB/Simulink and the losses of 200KVA transformer is then evaluated and results are compared.

Keywords: Harmonic loads, Proximity effect, Stray losses, Transformer model

Introduction

Increasing nonlinear loads, harmonic levels in distribution networks has greatly increased, and increases in harmonic load current cause additional losses and increases in winding hot spot temperature and stress on insulation and finally reducing the useful life of insulation and transformer capacity. The losses on transformer increase with the presence of harmonics. A more serious effect of harmonic loads served by transformers is due to an increase in eddy current losses. The eddy current losses increase appears as the square of the current in the conductor and the square of its frequency has a significant effect on the operating temperatures of the transformers [1]. The winding eddy currents are caused by two types of effects: skin effect and the proximity effect. It had been found that the skin effect is negligible when the skin-effect factor is smaller than two-for which windings and conductors are generally designed.

Several measures and development works on the effect of harmonic on losses of life of transformers have been conducted. Therefore, major effects of harmonic distortion are the increasing transformer losses. Losses that are affected by the harmonic current loadings are the I^2R loss, eddy current loss and the stray loss. In this paper, Simulation of Proximity Effect in Transformer Due To Harmonic Loads and results are compared.

Research Methodology

Transformer Losses:

Transformer losses under linear and harmonic loads are divided two categories no load and load loss[2]:

$$P_T=P_{NL}+P_{LL}$$

Where P_{LL} loading losses that is divided holmic losses and eddy loss, P_{NL} no load is due to voltage induced in the core and P_T is total loss of the transformer.

Load losses:

Load losses can be stated as follows:

$$P_{LL}=P_{DC}+P_{EC}+P_{OSL}$$

P_{DC} is ohmic loss due to coil resistance and P_{EC} eddy current losses and P_{OSL} other stray loss[2].

Eddy current losses in windings

There are two effects that can cause increase in winding eddy current losses in windings, namely the skin effect and the proximity effect. The winding eddy current loss in the power frequency Spectrum tends to be proportional to the square of the load current and the square of frequency which are due to both the skin effect and proximity effect,[10] i.e.

$$P_{EC}\,\alpha\, I^2 \times f^2$$

The impact of lower order of harmonics on the skin effect is negligible in the transformer Windings [3].

Proximity effect:

In a conductor carrying alternating current, if currents are flowing through one or more other nearby conductors, such as within a closely wound coil of wire, the distribution of current within the first conductor will be constrained to smaller regions. The resulting current crowding is termed the proximity effect. This crowding gives an increase in the effective resistance of the circuit, which increases with frequency.

A changing magnetic field will influence the distribution of an electric current flowing within an electrical conductor, by electromagnetic induction. When an alternating current (AC) flows through an isolated conductor, it creates an associated alternating magnetic field around it. The alternating magnetic field induces eddy currents adjacent conductors, altering the overall distribution of current flowing through them. The result is that the current is concentrated in the areas of the conductor furthest away from nearby conductors carrying current in the same direction. The proximity effect can significantly increase the AC resistance of adjacent conductors when compared to its resistance to a DC current. The effect increases with frequency. At higher frequencies, the AC resistance of a conductor can easily exceed ten times its DC resistance. The proximity effect loss can be expressed as[5]:

$$P_{pe} = \frac{\mu^2 N w^2 I^2 n d^4}{128 \rho l} Gr$$

Where, n is number of conductor strands, d is the strand diameter, and I is maximum current , G_r is proximity effect factor and by considering

$\delta = \sqrt{1/w\mu\sigma}$ $G \rightarrow 1$ as $\frac{d}{\delta}$ decreases to unity and when $\frac{d}{\delta}$ is increasing beyond 4[2].

At higher frequencies or with larger conductor diameters such that the ratio d/δ becomes larger than unity and field due to these eddy currents. The flux density inside the conductor is significantly reduced and associated current distribution becomes non-linear. The proximity effect can be reduced through a reduction of conductor diameter. Reducing the conductor diameter will increase the value of dc resistance and will result in greater overall loss. The power loss expression for the proximity effect on conductors for non sinusoidal currents can be written in terms of harmonic components in a general form as[6]:

$$P_{pe-h} = k \sum_{h=1}^{hmax} {w_h}^2 {I_h}^2$$

Or the proximity effect or eddy current losses in terms of per unit harmonic current values used more often in power system as[1]:

$$P_{pe} = P_{pe-R} \sum_{h=1}^{hmax} {w_h}^2 {I_h}^2$$

Therefore, proximity effect loss or winding eddy current loss is proportional to the square of the frequency.

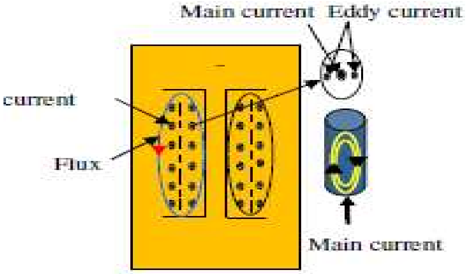

Fig.1 Proximity effect on eddy current[4].

Winding eddy current loss circuit parameter:

The computation of the proximity effect parameter by electromagnetic theory", the winding eddy current per unit, i_{ec}, is estimated for a transformer [7]as:

$$I_{ec}(pu) = \frac{d^2/dt^2 i_L}{d^2 \, i_R/dt^2}$$

The winding eddy current voltage can then be calculated in the general form for transformer as:

$$vec = i_{ec}(pu).I_{R-p} \times R_{EC-R}$$

The winding eddy current voltage, v_{ec} for the secondary or primary side referred. The winding eddy current loss resistance, R_{EC}, for the primary and secondary side in terms of winding eddy current loss, $P_{EC,}$ and rated current is expressed as:

$$R_{EC-R,1} = \frac{P_{EC,1}}{I^2 R_1}$$

$$R_{EC-R,2} = \frac{P_{EC,2}}{I^2 R_2}$$

The primary winding eddy current voltage, $vec_{,1}$, can then be expressed in terms of the winding eddy current resistance, $R_{EC-R,\ 1}$, at rated fundamental voltage, the rated peak to peak current, I_{R-pp}, of the transformer and the winding eddy current unit, i_{ec} *(pu).*

$$v_{ec,1}(pu) = i_{oc1}(pu).I_{R-p,1} \times R_{EC-R,1}$$

$$v_{ec.1}(pu) = \frac{I_{R-P,1} \times R_{EC-R,1}}{I_{R-P,1} w_1^2} \times \frac{d^2 i_1}{dt^2}$$

$$[R_{EC-R,1} = \frac{P_{EC-R,1}}{I_{R,1}^2}]$$

$$v_{ec,1}(pu) = k_{ec,1} \frac{d^2 i_1}{dt^2}$$

The secondary winding eddy current loss, vec$_1$, can be expressed similarly,

$$v_{ec,2}(\text{pu}) = i_{ec2}(\text{pu}).I_{R-p,2} \times R_{EC-R,2}$$

$$v_{ec,2}(pu) = \frac{I_{R-P,2} \times R_{EC-R,2}}{I_{R-P,2} w_2^2} \times \frac{d^2 i_2}{dt^2}$$

$$\left[R_{EC-R,2} = \frac{P_{EC-R,2}}{I_{R,2}^2}\right]$$

$$v_{ec,2}(pu) = k_{ec,2} \frac{d^2 i_2}{dt^2}$$

Other stray losses in transformer:

Each metallic conductor linked by the electromagnetic flux experiences an internally induced voltage that causes eddy currents to flow in that ferromagnetic material. The eddy currents produce losses that are dissipated in the form of heat, producing an additional temperature rise in the metallic parts over its surroundings. The eddy current losses outside the windings are the other stray losses. The other stray losses in the core, clamps and structural parts will increase at a rate proportional to the square of the load current but not at a rate proportional to the square of the frequency as in eddy current winding losses. Experiments were done to find the change of other stray losses with frequency. Results shown that the ac resistance of the other stray losses at low frequencies (0–360Hz) is equal to[8]:

$R_{OSL}=1.29(f_h/f_1)^{0.8} m\Omega$

And at high frequencies (420-1200Hz) the resistance is

$R_{OSL}=9.29-0.59(f_1/f_1)^{0.9} m\Omega$

Therefore, the other stray losses increase with power of 0.8 at low frequencies and decrease at high fre quency with power of 0.9.Thus this loss is proportional to square of the load current and the frequency to the power of 0.8. i.e .

$P_{OSL}=P_{TSL}-P_{EC}$

The other stray loss resistance for the primary and secondary side in terms of other stray loss at rated current can be derived [2]as:

$$R_{OSL-R,1} = \frac{P_{OSL-1}}{I_{1-R}^2}$$

$$R_{OSL-R,2} = \frac{P_{OSL-2}}{I_{2-R}^2}$$

Therefore, other stray loss resistances expressions can be used to series in the transformer electrical model.

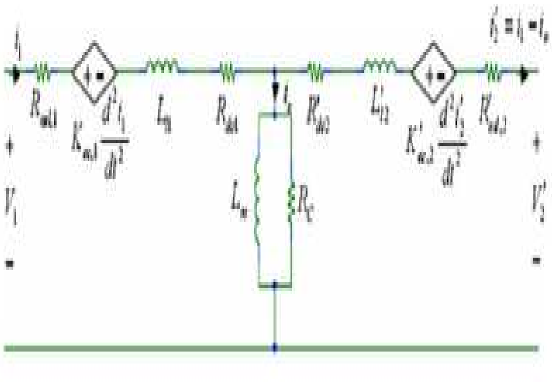

Fig.2.Proposed equivalent transformer model[8].

This is 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.

Data Analysis

Calculation of losses of transformer under harmonic loads:

This section, calculation and simulation of losses of transformer under harmonic loads will perform. Then results are compared.

Theoretical Calculation

200KVA, 11KV/440V transformer used in this paper.

The total stray loss, P_{TSL} can be calculated as:

$P_{TSL}=P_{SC}-P_{DC}=1000-968.4=31.6$watts

The winding eddy current loss and other stray loss are:

$P_{EC}=0.33\times(31.6)=10.42$watts

$P_{OSL}=31.6-10.42=21.18$watts

Harmonic Load Specification in table 1:

Harmonic order	**1**	**5**	**7**	**11**	**13**
Amplitude	**1**	**0.192**	**0.132**	**0.073**	**0.0057**

If transformer supplying a load with specification in table 1 losses on harmonic load calculated.

Experimental Results

For Simulation of the obtained transformer model, MATLAB/Simulink is used. In fig.2 shows the proposed model of transformer in MATLAB/Simulink. Current sources with different frequencies are put in parallel to model the harmonic load, as in table 2.Load power losses are determined through simulations and summarized in table 3.

Table 3. Losses under harmonic load by Simulation:

Types of losses	Rated losses(w)	P_{LL} Losses under rms harmonic load current(w)
No load	166.6	166.6
dc	968.4	994.9
Winding eddy current	10.4	113.4
Other stray	21.1	230.4
Total	1166.5	1505.3

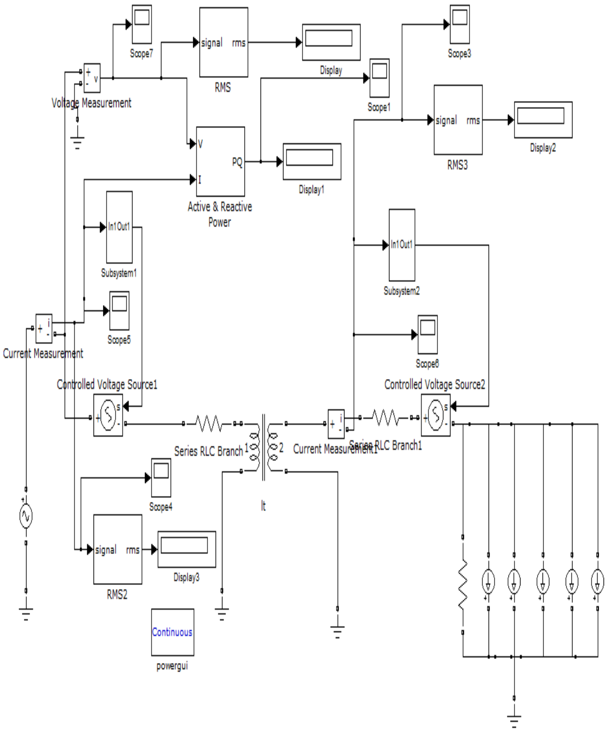

Fig.3 Proposed model in Simulink.

Conclusion

This paper has been shown that an increase of winding eddy current losses due to harmonic load currents can reduce the maximum allowable magnitude of the transformer load current. Although increased temperatures cause higher conduction losses, and winding eddy current losses tend to decrease with an increase in temperature. The proposed transformer model includes a parameter that estimates the winding eddy current loss in the transformer that results in a smaller loss in power capacity. A winding eddy-current loss that is high in magnitude results in a lower permissible load current which translates into a lower power capacity for the power transformer. The lower power capacity due to the lower permissible load current results in a loss of return on capital investment. Therefore a more accurate estimate on winding eddy-current loss was determined for the transformer, which shows a saving on power capacity.

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