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ESTIMATIVE STUDIES OF EDDY CURRENT CONSTANT (K_e) IN IRON LOSS OF A $400VA$ SINGLE PHASE TRANSFORMER USING VARIATIONS IN VOLTAGE AND FREQUENCY

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ABSTRACT
Losses are undesirable in power systems; thus it is the ultimate desire of a power engineer to obtain a stable and loss-free system. However, this is not realizable in practice. This is because losses exist in many forms ranging from the most common copper losses (I^2R) in cables in power system to other complex losses. In power transformers, losses exist in form of iron losses and copper losses. These copper losses exist in the windings of a transformer when current supplies the windings with resistance. Iron losses comprising the eddy current loss and hysteresis loss exist in a transformer when there are variations in frequency. In this paper, different values of the product of maximum flux density squared and frequency squared are obtained at five staged by varying the voltmetre, wattmetre, fluxmetre etc. in the apparati in fig.1. Also, a corresponding value of the eddy current value is computed as a percentage of the whole core losses in the wattmetre. A graph of the eddy current loss against the product of the maximum flux density squared and the frequency squared is obtained. The scope of the gradient gives an estimated value of the eddy current constant.

INTRODUCTION
Losses exist in a transformer in form of iron losses and copper losses. The existence of these losses contradicts the theoretical assumption of an ideal transformer which presents a transformer without any magnetic leakage, with one hundred percent efficiency, a transformer whose output is equal to the input suggesting that there are no losses in the transformer (Gupta, J. B., 2004).

Iron loss exists as a result of variation in frequency of the incoming voltage and also variation of the alternating flux. The iron losses can be broadly classified as (i) EDDY CURRENT and (ii) HYSTERESIS LOSSES (Nwosu, N. O. & Anierobi, P., 2020). It is necessary to know the source and concept of the eddy current in a circuit before proceeding to the study of the losses accompanying eddy current (Draper A., 1971).

Whenever there is a flux linkage with a close circuit and also when a path is introduced with a wire across the circuit, current flows in the circuit depending on the e.m.f. around the circuit. Now if there is no wire and the flux linkage is around a solid metallic block, the metallic circuit in the block itself which are linked by the flux will equal carrying currents. If the magnetic circuit itself is made of Iron and if the flux in the circuit is variable, currents are induced in the metallic Iron circuit itself. Such currents are known as eddy current (Nwosu, A. W. & Obi, P. I., 2009).

Now this eddy current results in a loss of power. This loss of power results in the heating up of the material during operation. For instance, it can be observed that an energized transformer becomes hot after some time of operation. This is as a result of eddy current loss (P_e) quantified as $(P_e) \propto Bmax^2 f^2$ i.e. $P_e = K_e Bmax^2 f^2$, where K_e is the eddy current constant, $Bmax$ is the magnetic flux density and f is the frequency of the source (Menhta, V. K, 2000).

In this paper, different variation of frequency, magnetic flux density and voltages are obtained from the operation of a $400VA$ single phase transformer. In each instant, different values of losses are estimated. The eddy current constant can be estimated from the graph of the different values of the product of the square of maximum flux density and square of the frequency. From the above equation, it is clear that the eddy current loss P_e (i) varies as the square of the maximum flux density (ii) varies as the square of the frequency (Adebayo, A. A., 2009).

DERIVING THE FLUX DENSITY $(Bmax)$ RELATION

Let's take a transformer with a core section of A_i and having N number of turns. Here we talk of variable frequency. If a voltage E_1 at a frequency f_1 is applied, then $E_1 = 4.44 f_1 N Bmax_1 A_i$ and if a voltage of E_2 at a frequency f_2 is applied, then $E_2 = 4.44 f_2 N Bmax_2 A_i$

$$Bmax_1 = \frac{E_1}{4.44 f_1 N A_i}$$
$$Bmax_2 = \frac{E_2}{4.44 f_2 N A_i}$$
$$\frac{Bmax_2}{Bmax_1} = \frac{E_2}{4.44 f_2 N A_i} \times \frac{4.44 f_1 N A_i}{E_1}$$
$$= \left[\frac{E_2}{E_1} \times \frac{f_1}{f_2}\right]$$

COPPER LOSS

The copper loss Pc in a power system is given by $Pc = I^2R$ where I is the supply current and R is the resistance in ohms.

$$Pc \propto I^2$$
$$\therefore \frac{Pc_2}{Pc_1} = \left[\frac{I_2}{I_1}\right]^2$$

HYSTERESIS LOSS (P_h)

The laminated iron core of a transformer is subjected to an alternating magnetizing force and for each cycle of e.m.f. a hysteresis loop is traced out. The hysteresis loss per second is given by the equation

Hysteresis loss $P_h = k_h(Bmax)^{1.6}f$; where k_h = hysteresis constant, $Bmax =$ maximum flux density and f is the supply frequency.

TRANSFORMER RATING (Q)

Transformers are always rated in KVA instead of watts. This is because this apparent power depends on the product of voltage and current i.e. ($Volt. Amps$). Also, the losses in the transformer depends on Volts and Amps. The iron loss depends on voltage whereas the copper loss depends on the current. Hence transformers are rated in VA or KVA. So, $\emptyset$ is the KVA rating of a transformer.

PERCENTAGE EDDY CURRENT LOSS (%Pe)

It is always desirable to determine the exact value of the eddy current loss from the total iron loss recorded by the wattmeter. As mentioned above, the total iron loss comprises the eddy current loss (Pe) and the hysteresis loss (P_h). By applying mathematical analysis, the percentage of each loss is determined.

Percentage eddy current loss $\%Pe = \frac{actual\ loss\ (Pe)}{Q} \times 100$

Where Q = rating of transformer in KVA

$$\%Pe \times Q = actual\ loss\ (Pe) \times 100$$

$$\therefore\ actual\ loss \propto \%Pe \times Q$$

So, $\frac{Pe_2}{Pe_1} = \frac{\%Pe_2 Q_2}{\%Pe_1 Q_1} = \frac{(Bmax_2)^2}{(Bmax_1)^2} \times \left[\frac{f_2}{f_1}\right]^2$

PERCENTAGE COPPER LOSS $(\%\boldsymbol{Pc})$

The percentage copper loss $\%Pc = \frac{actual\ loss}{Q} \times 100$

Then $\%Pc \times Q = actual\ loss\ \times 100$

It then follows that $[actual\ loss\ Pc] \propto \%Pc \times Q$

$$\therefore \frac{Pc_2}{Pc_1} = \left[\frac{I_2}{I_1}\right]^2 = \frac{\%Pc_2}{\%Pc_1} \times \frac{Q_2}{Q_1}$$

PERCENTAGE HYSTERESIS LOSS $(\%\boldsymbol{Ph})$

The percentage hysteresis loss $\%Ph = \frac{actual\ loss\ (Ph)}{Q} \times 100$

Then $\%Ph \times Q = actual\ loss\ Ph\ \times 100$

$\therefore actual\ loss \propto \%Ph \times 100$

$$\frac{Ph_2}{Ph_1} = \frac{\%Ph_2}{\%Ph_1} \times \frac{Q_2}{Q_1} = \left[\frac{Bmax_2}{Bmax_1}\right]^{1.6} \times \frac{f_2}{f_1}$$

MATERIALS & METHOD

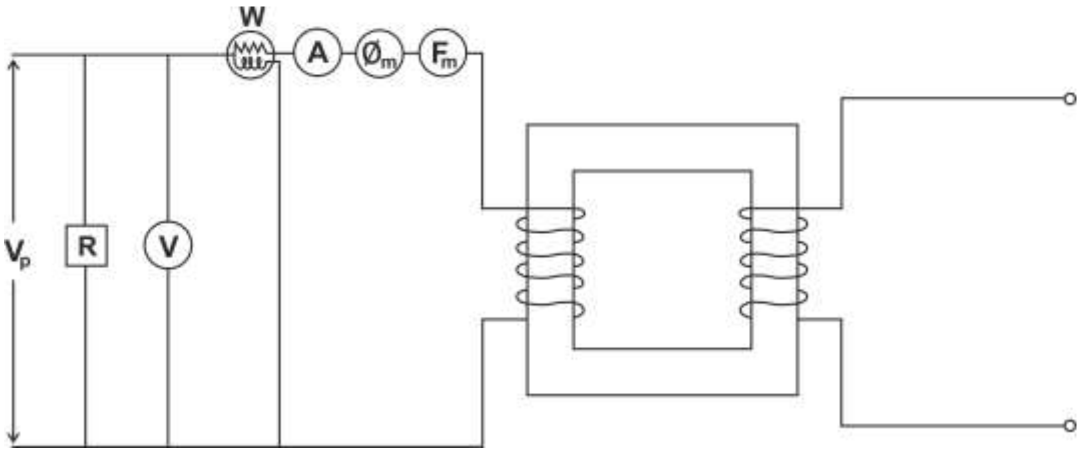
In this study, different values of the iron loss are recorded against values of the products of the maximum flux density and frequency of the alternating voltage used to energize an open circuit transformer. In this test, it is desired to obtain different values of core losses (iron losses) against different values of maximum flux density and frequency. This is obtained at five or six different steps. After obtaining the different values of the core losses, an estimated average value is obtained.

Since core loss comprises both the eddy current loss and hysteresis loss, an estimated value of eddy current loss is obtained by calculating the percentage eddy current loss in each value of core loss obtained at each instant of the test. To obtain different values of the core losses, the apparati below is set up.

Here, the high voltage winding of a transformer is left open and the other winding is connected to a supply of normal voltage and frequency. A regular wattmeter (w), voltmeter (v), and fluxmetre $(\emptyset)$, an ammeter and frequency metre (f) are connected as shown in fig.1.

In this test, variation in core loss is measured by the wattmeter. Since the wattmeter (w) records the total iron loss, the core loss in each step is got by subtracting the percentage eddy current loss from the total core loss recorded by the wattmeter in each instant. The product of the maximum flux density $(Bmax)$ and frequency at each instant is got by varying the incoming flux and voltage. This is obtained by the use of a regulator that consists of windings at different tappings representing resistances at different applied voltages different values of currents are obtained at different instant.

The different values of currents set up different magnetomotive forces (m.m.f) and hence different values of fluxes are obtained. Having known the area of cross-section of the transformer, the flux density in the transformer is recorded. Hence the maximum flux density is indicated by the fluxmetre. Also, varying the incoming voltage of the transformer will result to variation in the frequency. So the product of maximum flux density and frequency all squared at each instant is also computed. This is done for at least five instants and a graph is plotted. The gradient of the graph gives an estimated value of the eddy current constant (K_E).



The above apparati is set up as shown above in fig.1. R is the regulator consisting of various tappings of resistances in the coil. V is the voltmeter that records the applied voltages at various instants. (W) is the wattmeter that indicates the total iron losses in the core at various instants. (A) is the ammeter showing different values of varied currents, $(\emptyset_m)$ is the fluxmetre indicating the different values of flux in webers and consequently the maximum flux. (f_m) is the frequency metre indicating different varied frequencies.

By applying the voltage V_p and at normal frequency, the voltmeter V records the input voltage, the wattmeter, the ammeter (A), fluxmetre $(\emptyset_m)$ and frequency metre (f_m) indicate core loss, current, flux and frequency respectively at that instant. Hence, it is desired to vary the values of the parametres to obtain varied values of the losses against the product of the varied maximum flux density and frequency.

Now, increasing the resistance by adjusting the regulator will produce corresponding changes in core loss, current, flux and frequency. Increasing the resistance of the system will decrease the current in the circuit and vice versa. However, varying the current will produce varied values of the flux recorded by the fluxmetre. The maximum flux is obtained by the fluxmetre since the area of cross-section A_i of the transformer is constant. Varying the applied voltage produced varied values of the frequency as indicated by the frequency metre.

This test is conducted at five instants where varied values of the core losses are obtained against varied values of the products of maximum flux density and frequency all squared are obtained. The eddy current loss at each instant is computed as a percentage of the total core loss (comparing the eddy current loss and the hysteresis loss).

RESULTS

Varying the currents by adjusting the regulator produced different values of open circuit currents $I_\emptyset$, supplying different core losses. Also, varying the currents produced different values of magnetic flux recorded in the fluxmetre as the flux density. At every instant, the maximum flux density is also recorded in the fluxmetre. The different values of the eddy current loss (Pe) is computed as a percentage of the whole core loss in each instant. It is assumed that the percentage of the loss Pe is 50% the total loss.

The varying values of the applied voltage results in the varying values of the operating frequency. After about five different steps (instants) the eddy current loss values against the products of maximum flux density and frequency is obtained. The product of the maximum flux density raised to power 2 and frequency raised to power 2 is plotted against the eddy current loss.

Stage 1

$I_1 = 0.3A,\quad Vp_1 = 180V,\quad VpI_1 \cos\theta_1 = 280watts,\quad Bmax_1 = 0.9383\, wb/m^2,$

$f_1 = 50Hz,$

$Pe_1 = \text{eddy current loss in the first instant}$

$$= \frac{50}{100} \times 280$$

$$= 140watts.$$

Stage 2

$I_2 = 0.45A,\quad Vp_2 = 185V,\quad VpI_2 \cos\theta_2 = 300watts,\quad Bmax_2 = 0.9870\, wb/m^2,$

$f_2 = 60Hz,$

$Pe_2 = \text{percentage eddy current loss}$

$$= \frac{50}{100} \times 300$$

$$= 150watts.$$

Stage 3

$I_3 = 0.55A, \quad Vp_3 = 200V, \quad VpI_3 \cos\Theta_3 = 320watts, \quad Bmax_3 = 0.9989\, wb/m^2,$

$f_3 = 80Hz,$

$Pe_3 =$ percentage eddy current loss

$$= \frac{50}{100} \times 320$$

$$= 160watts.$$

Stage 4

$I_4 = 0.7A, \quad Vp_4 = 210V, \quad VpI_4 \cos\Theta_4 = 340watts, \quad Bmax_4 = 1.0983\, wb/m^2,$

$f_4 = 90Hz,$

$Pe_4 =$ percentage eddy current loss

$$= \frac{50}{100} \times 340$$

$$= 170watts.$$

Stage 5

$I_5 = 0.8A, \quad Vp_5 = 220V, \quad VpI_5 \cos\Theta_5 = 360watts, \quad Bmax_5 = 1.200\, wb/m^2,$

$f_5 = 100Hz,$

$Pe_5 =$ percentage eddy current loss

$$= \frac{50}{100} \times 360$$

$$= 180watts.$$

RESULT ANALYSIS

A table of values for the result is obtained below showing the different parameters varied at different stages (instants). I is the current, Vp is the applied voltage, $VpI \cos\Theta$ is the total core loss, where an assumed fifty percentage of it give us the eddy current loss. $Bmax$ is the maximum or peak value of the flux density, f is the supply frequency and Pe is the eddy current loss calculated at each stage from the total core loss. The subscript 1 to 5 are given to the different parametres being varied, to indicate the stage or the instant.

At the five stages, different values of the eddy current loss are obtained and marched against different values of the product of the maximum flux density and the frequency. On plotting the graph of the eddy current loss against the product of maximum flux density and frequency, all squared, a straight line is obtained. Below is a table of values for the results.

Table of Values

Stage 1

$I_1(A)$	$Vp_1(V)$	$Vp_1 \cos\theta_1 (w)$	$Bmax_1(T)$	$f_1(Hz)$	$Pe_1(watts)$
$\mathbf{0.3}$	180	280	0.9383	50	140

Stage 2

$I_2(A)$	$Vp_2(V)$	$Vp_2 \cos\theta_2 (w)$	$Bmax_2(T)$	$f_2(Hz)$	$Pe_2(watts)$
$\mathbf{0.45}$	185	300	0.9870	60	150

Stage 3

$I_3(A)$	$Vp_3(V)$	$Vp_3 \cos\theta_3 (w)$	$Bmax_3(T)$	$f_3(Hz)$	$Pe_3(watts)$
$\mathbf{0.55}$	200	320	0.9989	80	160

Stage 4

$I_4(A)$	$Vp_4(V)$	$Vp_4 \cos\theta_4 (w)$	$Bmax_4(T)$	$f_4(Hz)$	$Pe_4(watts)$
$\mathbf{0.7}$	210	340	1.0983	90	170

Stage 5

$I_5(A)$	$Vp_5(V)$	$Vp_5 \cos\theta_5 (w)$	$Bmax_5(T)$	$f_5(Hz)$	$Pe_5(watts)$
$\mathbf{0.8}$	220	360	1.200	100	180

CONCLUSION

The knowledge of losses in transformer and power system is desirable. It is a common practice that power is transmitted at a very high voltage and low current. This is done to minimize power loss in form of copper (I^2R) loss.

In transformer systems, the knowledge of the losses helps in improving the efficiency of the system. the existence of these losses contradicts the theory of the ideal transformer that assumes a hundred percent efficiency. Also, the knowledge of these losses helps in improving the efficiency and voltage regulation of a system. A transformer is a very highly efficient machine. This is because a transformer is static and has no rotating parts. The inherent losses – the copper loss and iron loss are very minimal. This knowledge helps in determining the efficiency of a particular rated transformer.

Parts of a consumer's electricity charges are due to losses along the cable i.e. I^2R loss. A consumer is mandated to pay charges in his peak demand in KVA in addition to the units consumed. A knowledge of the losses equips a power engineer with facts of his power consumption.

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