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Measurement and Calculation of Loss in the Transformer Core due to the Hysteresis and Eddy Current Losses

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Abstract

Most of the problems which impede the transformer designers are the power losses in the iron core due to the eddy current and the hysteresis phenomena. The aim of this study is to measure and discuss the total loss for the small step down transformer which was brought from the local market to the (HISTZ - 305) lab. The results showed a good agreement between the calculations and the measured values

Keywords: transformer, hysteresis losses, eddy current losses, measurement, magnetic density.

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قياس و حساب الفقد في القلب الحديدي للمحول الكهربي الناتج من تاثير التخلف المغناطيسي والتيارات الدوامية

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الملخص

معظم المشاكل التي تعيق مصممي المحولات الكهربية هي المفاقيد الحرارية في القلب الحديدي والناتجة من تأثير التيارات الدوامية وظاهرة التخلف المغناطيسي والمسببة لتمغنط القلب الحديد بالمحول الكهربي وهذه المفاقيد تظهر علي شكل حرارة. ان الهدف من هذه الدراسة هو حساب وقياس المفاقيد الحرارية لمحول كهربي صغير خافض للجهد قد جلب من السوق لمعمل الكهربية 305 بالمعهد العالي للعلوم والتقنية بالزاوية. تشير النتائج إلي وجود توافق جيد بين النتائج المحسوبة و المقاسة.

الكلمات المفتاحية: محول كهربي، فقد التخلف المغناطيسي، فقد التيارات الدوامية، القياسات، الكثافة المغناطيسية.

1- Introduction

Most of the problems which impede the transformer designers are the total power losses. There are two types of losses take place in the electric transformer, the first one are at the No load (hysteresis loss, eddy current loss and dielectric loss) and second one are at the load (the copper loss and the stray loss), also leakage the magnetic flux considered as losses in the core. This study focuses in the iron core losses that are due to the eddy current and the hysteresis phenomena. In this paper small step down transformer TC- 8708299A (230 → 24, 12 volt, 50Hz) was brought from the local market to the (HISTZ - 305) lab. That is to measure and

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calculate the total Power loss in the iron core in the transformer then compares the results between them.

2- Literature review

Hysteresis losses and eddy current losses was investigated and discussed by many authors, for example: - Pof P. Parthasaradhy worked done in determining the hysteresis and eddy current losses of a magnetic material using Epstein frame [1]. J. Reinert discussed the influence of non sinusoidal flux wave forms on the re-magnetization loss in ferro – and ferrimagnetic material of induction and transformer [2]. KATSUMI YAMAZAKI proposed and investigated the method of calculating the losses of induction motors involving iron loss [3]. Andreas kings presents a short introduction on different methods to characterize magnetic materials for characterizing ring core samples [4]. Kabuli investigated the effects of flux and torque hysteresis bands on inverter switching loss, harmonic loss and torque ripple of induction motor, the influences of the values of the hysteresis band is the best and the hysteresis band respected to the values for DTC [5]. Guillaume Parent characterized experimentally the magnetic properties of grain oriented electrical steel in the rolling direction [6]. Mario Baussmann measured the magnetic characteristics of the transformer cores and coil material [7]. Zoltan NEMETH used an Epstein frame to measure magnetic properties of different kind of cores [8]. Bilal A. Nasir proposed a new model for iron core loss calculation of induction machines [9]. Authors researched and investigated the experimental characterizing of the magnetic properties using an Epstein frame [10 - 11].

3- The B–H carve

Hysteresis phenomena take place in ferromagnetic materials, if there is a ferrite ring has two windings, primary and secondary. The primary is fed to AC current I this leads to make a magnetic field H proportional to I, this is called Ampere's law:

$$\oint \boldsymbol{H} \cdot d\boldsymbol{l} = I_{enc} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

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On the other hand in the secondary coil the magnetic field H induces voltage e proportional to the flux density $\frac{d\Phi}{dt}$ which is called faraday's law:

$$e = \oint \boldsymbol{E} . d\boldsymbol{l} = -\frac{d\Phi}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Figure (1) illustrates the operations within a ferrite ring:-

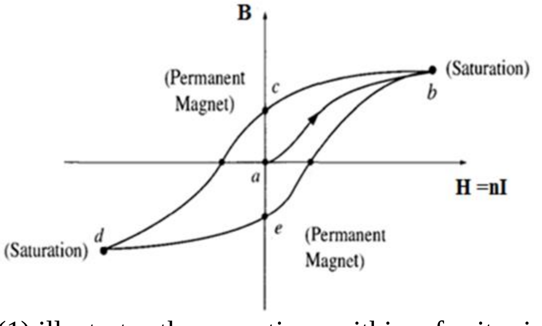

Figure (1) illustrates the operations within a ferrite ring [12]

The operations maybe explained as follows: 1- at the beginning in the un magnetized iron core (at a point), the current increase in the primary coil until I or H has the value corresponding to point b, 2, the current in the primary coil reduce back to zero (at c point), 3 reverse the current and increase it in magnitude until point d is reached, 4 the current reduce to zero again (at e point), 5 reverse the current once more until point b is reached again. The operation which is shown in figure (1) is called *hysteresis*. At the point c and e the iron core is magnetized, even though there is no current in the ring [13]. Consequently, the hysteresis effect generates heating inside the iron core and it can be measured. If we re-write again, the last two Maxwell equations:

$$HL = NI \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Or $$I = \frac{HL}{N} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

And $$e = -N\frac{d\Phi}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

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Or $$e = -N\frac{dBA}{dt} \quad \ldots\ldots (6)$$

Where: A is the area cross section, L is the magnetic path length then the power delivered is:

$$P = I\,V \quad \ldots\ldots (7)$$

Which is the *Joule heating law*.
Where: V in volts, and I in amperes, then P with watts [12].
By substitution equations (4, 6) in equation (7) where: $e = V$ we get:

$$P = \frac{HL}{N} \times \frac{N\,A\,dB}{dt} \quad \ldots\ldots (8)$$

So the power delivered maybe writes as:

$$P = \frac{dw}{dt} \quad \ldots\ldots (9)$$

The work done or the energy due to the hysteresis phenomena maybe writes as:

$$w = \int dw \quad = AL \int HdB \quad \text{(Joule)} \quad \ldots\ldots (10)$$

The integral $\int HdB$ is the total area enclosed by the hysteresis loop on the B–H carves and it can measure directly from the hysteresis loop at the screen of the oscilloscope using a transparent graph paper [1]. Furthermore, the phase shift between the current in the primary winding and the secondary induced voltage of the transformer also is related to the iron loss [2].

4- Calculate the Power loss of the iron core in the transformer
In order to calculate the total Power loss in the iron core in the transformer it must be calculate two losses:
The loss due to the hysteresis phenomena which can be use the empirical equation, which so-called Steinmetz methods:

$$P_h = k_h \, f^{\alpha} \, B_m^{\beta} \quad \ldots\ldots (11)$$

Where: k_h , α , β are empirical parameters which, $1 < \alpha < 3$, $2 < \beta < 3$ in fact the induction exponent of β in the equation has a typical value, $\beta = 2.5$. Then:B_m is the maximum of flux density, and f is the frequency [2].
The Eddy current loss which takes place within the core due to the change in the flux density of the magnetic field, this is called faraday's law so that, the eddy current loss can computed by the equation (12) as follows:

$$P_e = k_e \; B_m^2 \; f^2 \quad \ldots\ldots (12)$$

The constant k_e of this equation is depends on the cross section and the conductivity of the core. Physically there is no different between *hysteresis* losses and *eddy current* losses. Consequently, the hysteresis losses and eddy current losses are lumped together as the total Power loss. So that it can use the equation (13) to know the heat losses in the iron core [2].

$$w_i = k_e \, f^2 \, B_m^2 + \; k_h \;\; f^{\alpha} \, B_m^{\beta} \quad \ldots\ldots (13)$$

The last equation of the iron loss per unit weight can be expressed approximately as follows:

$$w_i = k_e \, f^2 \, B_m^2 + \; k_h \;\; f \, B_m^2 \quad \ldots\ldots (14)$$

Therefore, B_m can be determine by measure induced voltage e in the second winding which is proportional to the magnetic flux intensity, the frequency f also may be known firstly, and the coefficients of the iron loss k_e , k_h may be obtained from the data sheet of the transformer [3].

5- The Experimental setup

The measurement system is shown in figure (2). The used transformer is a small step down transformer (230 ⇢ 24, 12 volt,

50Hz), which has two outputs in the secondary windings 24, 12 volt. The Primary winding was connected to AC –Source with R_1 resistance in series connection, and the used Oscilloscope is connected across the shunt resistor R_1 with its horizontal channel. To calculate the magnetic field strength H, the current I, which is fed to the primary coil, needs to be measured.
In the secondary windings, once connected to the output of 12 volts then to the vertical channel of the Oscilloscope that is to calculate the magnetic flux density B_m which needs to measure the secondary voltage e using the equation (15):

$$B_m = \frac{e}{2\pi\, f\, N_2\ \ A} \quad \ldots\ldots (15)$$

Where: B_m is the magnetic flux density in tesla unit (T), $e = v_2$ in volt unit, f is the frequency, N_2 is the No. of turns of the secondary winding and A is the area cross section of the limb iron.
The experiment results are shown in figure (3). The experiment was repeated once again using the output of 24 volt, and the results are illustrated in figure (4).
In both experiments, the Oscilloscope was adjusted to work on the x-y mode. The hysteresis loop appears and formed at the screen. So that, by tracing the area of the hysteresis loop using a transparent graph paper, the heat losses can be measured.

Figure (2) the test rig of the experimental setup

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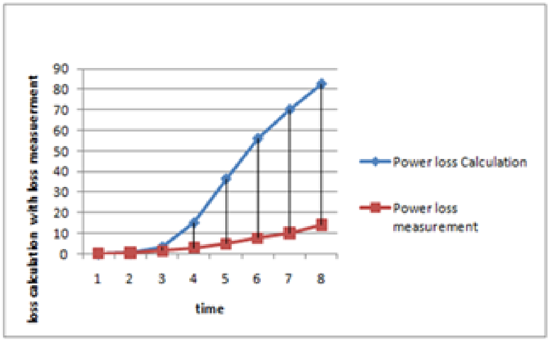

Figure (3) comparison between the measurement and the calculation losses in case of the output of 12volt

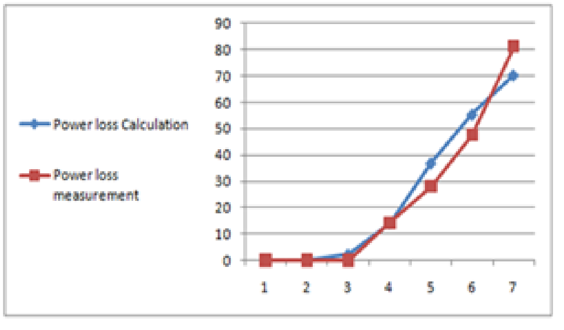

Figure (4) comparison between the measurement and the calculation losses in case of the output of 24volt

6- The Experimental Procedure

6-1- Determine the coefficients of the iron loss

If there is no geometrical information about the transformer like the coefficients of the iron loss or the number of the turns in both side of the transformer, in that case it can be compute the coefficients of the iron loss using the approximate equation in another expressed (divided each hand by the frequency f):

$$\frac{w_i}{f} = k_e \ B_m^2 \ f + \ k_h \ B_m^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Hence the relation between: $\frac{w_i}{f}$ and f must be linear. So that, the coefficients k_e , k_h may be obtained from the slope and from the intercept of the straight linear [3]. Experimentally, to know the coefficients of the iron core, the transformer was cabled to the Function Generator as a power supply, using some modifications making on the system tools, that's, to show the Influence of the frequency variation on the losses. Figure (5) shows the comparison between the variations of the frequency with increasing the losses, thus, the results were expected so that, any increase in the frequency leads to increase in the losses.

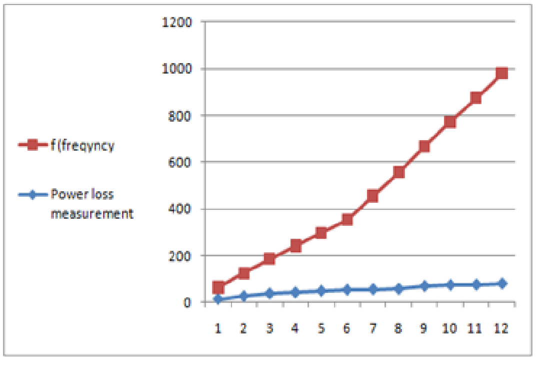

Figure (5) Influence of the frequency variation on the losses

Consequently, figure (6) illustrates the relation between the frequency f and the losses divided by the frequency $\frac{w_i}{f}$. The results shows that, the hysteresis coefficient, approximately is $k_h = 2.9 \times 10^{-2}$ and the eddy current coefficient is $k_e = 3 \times 10^{-5}$.

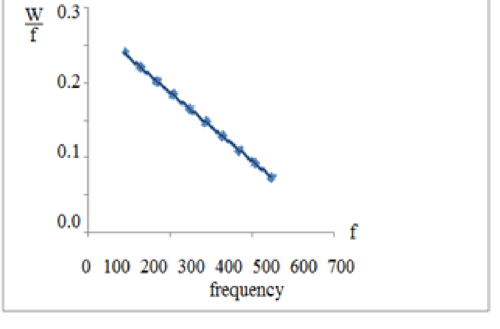

Figure (6). Determine the coefficients of the iron loss experimentally

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6-2- Determine the number of turns in both side of the transformer

In the transformer, the applied voltage is giving by:

$$v = \sqrt{2}\,\pi \text{ f N B A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(17)}$$

For N = 1turn, $v = 1\ volt$, f = 50Hs, B = 1tesla and $\sqrt{2}\,\pi$ = 4.44 then the area of the cross section A of the transformer by substitute in equation (17) is:

$$A = \frac{1}{4.44 \times 50 \times 1 \times 1} = 0.00450\ m^2 \quad = 45\ cm^2$$

By measure the area of the cross section of the transformer under the study, the applied voltage then the number of turns can be computed. According to this ratio: $1\ volt \ \dashrightarrow\ 45\ cm^2$. So that, in our case $12\ volt \ \dashrightarrow\ 6.67\ cm^2$ and divided by each other we get:

$$\frac{1\ turn}{1v} = \frac{45}{6.67} = 6.74$$

Then:

$$\text{N no.}/12 = 6.74 \times 12 = 80\ turns$$

Also from the relation: $\frac{e_2}{e_1} = \frac{N_2}{N_1}$ it can be obtained the number of turns of the other side [12].

7- Experimental Results and discussion

Data were collected, tabulated and treatment mathematically using the above equations with Excel programs. The output results were the relation between the measurement and the calculation losses, the magnetic field strength H, magnetic density and the Influence of the frequency variation on the losses. According to figure (5) the losses of the iron core are slightly increase with increasing the value of the frequency. As shown in figure (7) the values of the magnetic field strength H are greater than the values of the magnetic density B, this means there were some losses in the flux.

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Figure (8) supports the relation between the losses with the flux density as well as in figure (7). If we come back to Figures (3, 4), Figure (4) illustrates the comparison between the measurement and the calculation losses, the results shows that, there are an excellent agreement between two carves but in figure (3) the results shows that, there are some different value at the end of curves but it's good agreement at the beginning, this different maybe because there is some error take place with reading the experimental values.

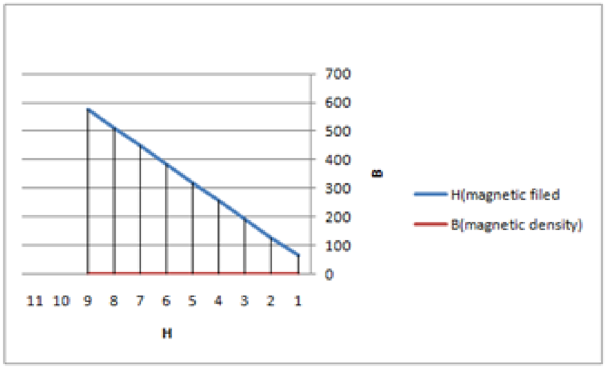

Figure (7) comparison between the magnetic field (H) with the magnetic density (B)

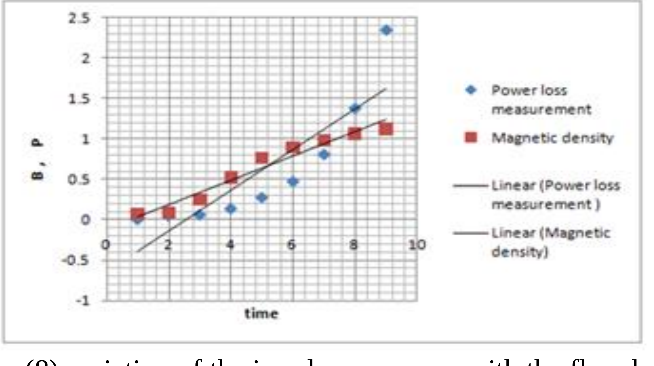

Figure (8) variation of the iron losses versus with the flux density

5- Conclusion

The experimental was discussed the relation between the measurement of the heat losses due to hysteresis and Eddy current

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with the flux density as well as comparing with the calculation loss. We can abbreviate the conclusion as following:

1- In case of the output of 24 volt the results were indicated that the comparison was excellent agreement between the two carves.
2- In case of the output of 12 volt, the results were appeared some different values in the two carves that maybe because there were some mistake reading causes when recording the experimental values.
3- The results of the influence of the variation of the frequency on the increasing of the losses were expected so that, any increased in the frequency leads to increase in the losses.
4- The different between the values of the magnetic field strength and the magnetic density due to the Eddy currents and hysteresis phenomena explained the strong relation between the losses and the magnetic density.

Acknowledgements
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