

Hysteresis and eddy current losses of magnetic material by Epstein frame method-novel approach

Prof P.Parthasaradhy, Dr S.V.Ranganayakulu

¹, Department of EEE, Gurunanak Institutions Technical Campus, Ibrahimpatnam, RangaReddy Dist, India
Email: ad.ps@gniindia.org

², Center for Non Destructive Evaluation, Innovation Centre, Gurunanak Institutions Technical Campus, Ibrahimpatnam, RangaReddy Dist, India.
Email:natakulu@rediffmail.com

-----ABSTRACT-----

This paper deals with the result of the work done in determining the Hysteresis and Eddy current losses of a magnetic material using Epstein frame. This paper deals with all about construction of Epstein frame using a particular magnetic material and tracing its Hysteresis loop in a CRO, (Cathode-Ray Oscilloscope) with the help of values obtained from the CRO the losses are calculated

KEYWORDS : Hysteresis losses, Eddy current losses, Epstein frame, Hysteresis loop.

I. INTRODUCTION

Designer of the transformer must know the iron losses i.e. the Hysteresis and Eddy current losses of the magnetic material used for the construction of the core of the transformer. Determination of iron losses using Epstein frame is one of the easiest and economical method which does not require rigorous design and complicated calculations. M. S. Lancarotte, A. d. A. Penteado Jr., and São Paulo, has been carried out [2] on "Prediction of magnetic losses under sinusoidal or nonsinusoidal induction by analysis of magnetization rate. M. Amar and R. Kaczmarek has been carried out [3] on "A general formula for prediction of iron losses under nonsinusoidal voltage waveform. Zhigang Zhao and coworkers have been carried out [7] on "Measurement and Calculation of Core – Based B-H Curve and Magnetizing Current in DC – Biased Transformers". John B. Good enough has been carried out [8] on "Summary of Losses in Magnetic Materials. Aldo Boglietti and coworkers have been carried out [10] on "Predicting Iron Losses in Soft Magnetic Materials with Arbitrary Voltage Supply". Kabil Venkatachalam, Charles R. Sullivan, Tarek Abdallah, and Hernan Tacca have been carried out [11] on "Accurate Prediction of Ferrite Core Losses with Nonsinusoidal Waveforms Using Only Steinmetz Parameters". Simon Steentjes, Georg von Pflingsten, Macro Hombitzer, and Kay Hameyer have been carried out [12] on "Iron-Loss Model With Consideration of Minor Loops Applied to FE-Simulations of Electrical Machines. Yu Zhang has been carried out [13] on "Magnetic Characteristics and Core Losses in Machine Laminations: High –Frequency Loss Prediction from Low-Frequency Measurements". Maged Ibrahim and Pragesen Pillay have been carried [14] on "Novel Equipment for the Measurement of Core Losses in Laminations for Advanced Machines".

II. DETERMINATION OF LOSSES

The losses that can occur in a material are:

Iron losses: Iron loss is caused by the alternating flux in the core and consists of hysteresis and eddy current losses.

Hysteresis Loss: Hysteresis loss is associated with the phenomena of hysteresis and is an expression of the fact when ferromagnetic material is involved, not all the energy of the magnetic field is returned to the circuit when mmf is removed. It is known as hysteresis loss. The core of a transformer is subjected to an alternating magnetizing force and for each cycle of emf a hysteresis loop is traced out. A great deal of information can be learned about the magnetic properties of a material by studying its hysteresis loop [16]. A hysteresis loop shows the relationship between the induced magnetic flux density (B) and the magnetizing force (H). It is often referred to as the B-H loop. An example hysteresis loop is shown below.

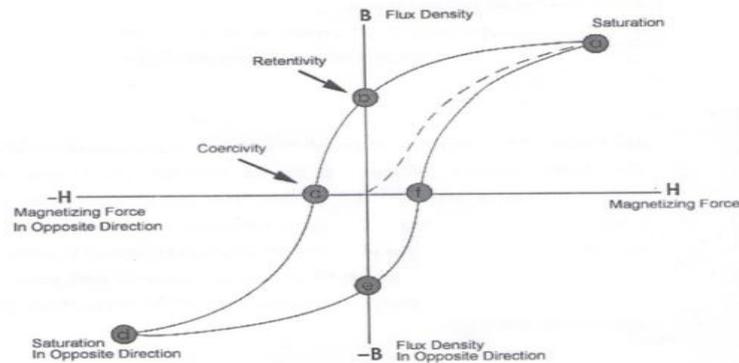


Figure 1: hysteresis loss

The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as **H** is increased. As the line demonstrates, the greater the amount of current applied (**H**+), the stronger the magnetic field in the component (**B**+). At point “a” almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux. The material has reached the point of magnetic saturation. When **H** is reduced to zero, the curve will move from point “a” to point “b”. At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates the remanence or level of residual magnetism in the material. As the magnetizing force is reversed, the curve moves to point “c”, where the flux has been reduced to zero. This is called the point of coercivity on the curve. (The reversed magnetizing force has flipped enough of the domains so that the net flux within the material is zero.) The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material. As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction (point “d”). Reducing **H** to zero brings the curve to point “e”. It will have a level of residual magnetism equal to that achieved in the other direction. Increasing **H** back in the positive direction will return **B** to zero. Notice that the curve did not return to the origin of the graph because some force point “f” back to the saturation point where it will complete the loop. the mathematical model can be developed [15].

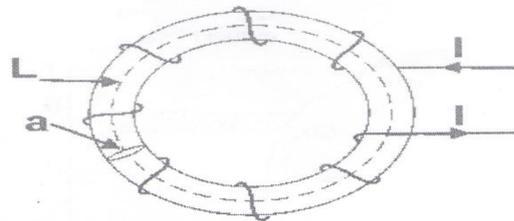


Figure .2: ferromagnetic specimen

Consider a ring of ferromagnetic specimen of circumference ‘L’ meter, cross sectional area ‘a’ m² and ‘N’ turns of insulated wire as shown in the figure above.

Let us consider, the electric current flowing through the coil is ‘I’ amperes. Magnetizing force is given as:

$$H = \frac{NI}{L} \text{ or } I = \frac{HL}{N}$$

Let the flux at this instant is ‘B’.

Therefore, total flux through the ring, $\Phi = B \times a$ Weber’s.

As the electric current flowing through the solenoid is alternating, the flux produced in the iron ring is also alternating in nature, so the emf (e’) induced will be expressed as,

$$\begin{aligned} e' &= -N \frac{d\Phi}{dt} \\ &= -N \frac{d}{dt}(Ba) \\ &= -Na \frac{dB}{dt} \end{aligned}$$

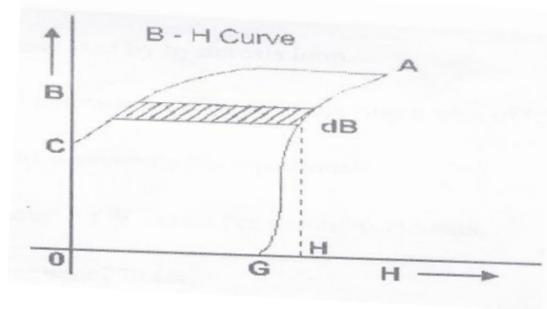


Figure 3: B-H curve

According to Lenz law this induced emf will oppose the flow of electric current, therefore, in order to maintain the current I in the coil, the source must supply an equal and opposite emf. Hence applied emf,

$$e = e' = Na \frac{dB}{dt}$$

Energy consumed in short time dt, during which the flux density has changed,

$$\begin{aligned} &= e.I.dt \\ &= Na \frac{dB}{dt} \times I \times dt \\ &= Na \frac{dB}{dt} \times \frac{HL}{N} \times dt = a.L.H.dB \text{ joules} \end{aligned}$$

Thus, total work done or energy consumed during one complete cycle of magnetism,

$$W = aL \int_0^{B_{max}} H.dB \quad (1)$$

Now 'aL' is the volume of the ring and 'H.dB' is the area of elementary strip of B-H curve shown in the figure above,

$$\int H.dB = \text{total area enclosed by hysteresis loop.}$$

Therefore, Energy consumed per cycle = volume of the ring x area of hysteresis loop.

The hysteresis loss per second is given by the equation[20]:

Hysteresis loss, $Ph = \eta'(B_{max})^{1.6} f$ V joules per second (or) watts.

Where, f: supply frequency in Hz,

V: volume of core in cubic meters,

η' : hysteresis coefficient,

B_{max} : peak value of flux density in the core.

Hysteresis loss can be obtained by Steinmetz method [29], according to which hysteresis loss per cubic meter per cycle of magnetization of magnetic material depends upon:

(i) The maximum value of flux density,

(ii) The magnetic quality of the material.

Therefore, (hysteresis loss) $\propto (B_{max})^{1.6} \text{ j/m}^3/\text{cycle}$

Hysteresis loss = $\eta (B_{max})^{1.6} \text{ j/m}^3/\text{cycle}$

$$= \eta (B_{max})^{1.6} f V \text{ j/s (or) watts.} \quad (2)$$

Where,

η = is a constant for given specimen and a given range of flux density and is known as Steinmetz constant,

f = frequency of reversals of magnetization,

V = volume of magnetic material in m^3 .

Eddy current losses: These losses arise from the fact that the core itself is composed of conducting material, so that the voltage induced in it by the varying flux produces circulating currents in the material. These are called eddy currents and are accompanied by ' i^2r ' loss in the core called eddy current loss.

Since the eddy current loss depends upon the rate of change of flux as well as the resistance of the path, it is reasonable to expect this loss to vary as the square of both the maximum flux density and frequency [18].

$$\text{Therefore, Eddy current loss, } P_e = K_e f^2 (B_{\max})^2 t^2 V \text{ watts (or) J/s.} \quad (3)$$

Where, K_e = eddy current coefficient, it depends upon type of core material,

f = number of complete magnetization cycles per second,

B_{\max} = maximum flux density in Teslas (Wb/m^2),

t = thickness of laminations in meters,

V = volume of core material in m^3 .

Eddy currents result in a loss of power, with consequent heating of the material.

Eddy current loss can be computed as follows:

Consider a lamination of transformer of length ' l ' meters width ' w ' meters, thickness ' t ' meters and carrying an alternating flux of density given $B = B_{\max} \sin \omega t$ passing in the direction of the arrow and parallel to the plane of the sheet. Eddy current will tend to flow around through the sheets in paths similar to the one drawn on the face of the lamination. Taking thickness of the lamination very small in comparison to its width, these paths may be considered as parallel to surface of the sheet. Consider an elemental path at a distance ' x ' from the center line of the sheet. Let the thickness of the path be ' dx '. The flux enclosed in this elemental path at any instant,

$$\begin{aligned} \Phi_x &= 2xw B_{\max} \sin \omega t \\ &= 2xw B_{\max} \sin 2\pi f t \quad (\text{since } \omega = 2\pi f) \end{aligned}$$

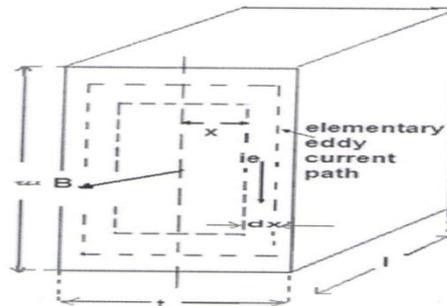


Figure 4: Lamination carrying alternating flux

The emf induced in this portion of elemental path,

$$\begin{aligned} E_x &= d\Phi_x/dt = d(2xw B_{\max} \sin 2\pi f t) / dt \text{ volts} \\ &= 4\pi xw f B_{\max} \cos 2\pi f t \text{ volts} \end{aligned}$$

The rms value of this induced emf,

$$\begin{aligned} E_x &= (4\pi f w x B_{\max}) / \sqrt{2} \text{ volts} \\ &= 2\sqrt{2} \pi x w f B_{\max} \text{ volts} \end{aligned} \quad (4)$$

The resistance of this portion of the path,

$$R = \rho \times 2w / l \, dx \text{ ohms, where } \rho \text{ is the resistivity of the material in ohm-meter.}$$

Neglecting the end portions of the path, the magnitude of eddy current is given by:

$$i_x = E_x / R = (2\sqrt{2} \pi x w f B_{\max}) / (2\rho w / l \, dx)$$

$$= (\sqrt{2} \pi f x B_{max} l dx) \rho \text{ amperes} \quad (5)$$

Eddy current loss, $P_x = (ix)^2 R$

$$ix = E_x / R = (2\sqrt{2} xfw B_{max}) / (2\rho w / l dx)$$

$$= (\sqrt{2} \pi f x B_{max} l dx) \rho \text{ amperes}$$

Eddy current loss, $P_x = (ix)^2 R$

$$= (\sqrt{2} x \pi f B_{max} l dx / \rho)^2 \times (2\rho w / l dx) \text{ watts}$$

$$= (4\pi^2 f^2 B_{max}^2 l w x^2) dx / \rho \text{ watts} \quad (6)$$

Total eddy current loss, $P_e = \int_{x=0}^{x=t/2} P_x$

$$P_e = \int_{x=0}^{x=t/2} (4\pi^2 f^2 B_{max}^2 l w x^2 dx) / \rho$$

$$= (\pi^2 f^2 B_{max}^2 l w t^3) / 6\rho$$

$$= (\pi^2 B_{max}^2 f^2 t^2 \text{ volume of lamination}) / 6\rho$$

{Since volume of lamination = wlt}

$$\text{Eddy current loss per unit volume} = (\pi^2 B_{max}^2 f^2 t^2) / 6\rho \text{ watts.} \quad (7)$$

To find the hysteresis losses in a transformer core:

We know that, in a transformer, the applied voltage ‘v’ is given by

$$V = \sqrt{2} \pi f n \Phi_{max} = \sqrt{2} \pi f n B_m A_i$$

$$B_m = \frac{v}{\sqrt{2} \pi f n A_i}$$

$$B_m = \frac{230}{\sqrt{2} \pi (50)(1200)(1.0 \times 10^{-3})}$$

$$B_m = 0.8 \text{ Tesla}$$

$$W_h = \text{Hysteresis Loss} = K_h \times f \times B_m^{1.6} \text{ watts}$$

$$W_h = 0.8 \text{ mill : watts}$$

S No.	Voltage (volts)	B _{max} (Tesla)	H (webers)	Hysteresis loss W _h (watts)
1	20	0.22	1.5	0.0041
2	40	0.43	2.22	0.0547
3	60	0.55	3.47	0.0886
4	80	0.60	5.55	0.0923
5	100	0.71	6.66	0.1547
6	120	0.74	9.13	0.1938
7	140	0.85	13.33	0.2564
8	160	1.15	15.24	0.3919
9	180	1.27	18.47	0.4879
10	200	1.28	19.33	0.7666
11	220	2.14	20.3	0.888
12	240	3.19	25.69	1.123

Table 1: calculating the hysteresis losses in transformer core

III. WORKING OF OPERATION

The primary winding of the Epstein frame is connected to a 1 – φ auto – transformer with an input of 230V, 50Hz as shown in the circuit diagram (fig.3.3).The secondary side of the Epstein frame is connected to a RC integrator with 10k and 1% resistor followed by a 0.22uF polyester film capacitor. The CRO probe is connected across the capacitor to obtain B – H curve. Before switching on the single phase variac the CRO must be set in swap mode. A dot appears on the display of the CRO which must be set to the center When the single phase variac is switched on we can observe a parabola on the display of the CRO which slowly converts into a leaf like structure (B – H Loop) with the increase in voltage. The unit enables one to trace the B-H loop (hysteresis) of a ferromagnetic specimen using a Cathode Ray Oscilloscope. A measurement of the area of the loop leads to the evaluation of energy loss in the specimen [19].

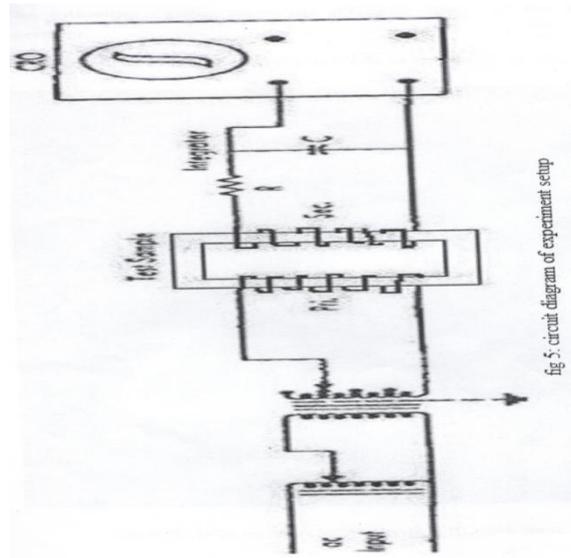


Figure 5: Circuit Diagram of Experiment setup
The experimental arrangement is shown in the figure given below:

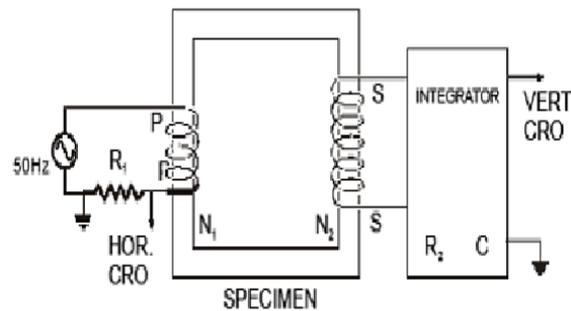


Figure 6: Transformer core arrangement.

One of the specimens used in the unit is made using transformer stampings. There are two windings on the specimen (primary and secondary). The primary is fed to low A.C. voltage (50 Hz). This produces a magnetic field H in the specimen. The voltage across R_1 (resistance connected in series with the primary) is proportional to the magnetic field. It is given to the horizontal input of the CRO. The A.C. magnetic field induces a voltage in the secondary coil. The voltage induced is proportional to $\frac{dB}{dt}$ (B -flux density). This voltage is applied to a passive integrating circuit. The output of the integrator is proportional to B and fed to the vertical input of the CRO. As a result of the application of a voltage proportional to H to the horizontal (input) axis and a voltage proportional to B to the vertical (input) axis, the loop is formed as shown in the figure below.

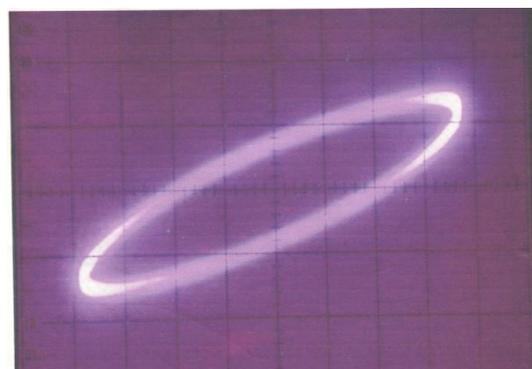


Figure 7: B-H curve obtained with CRO connected across the capacitor

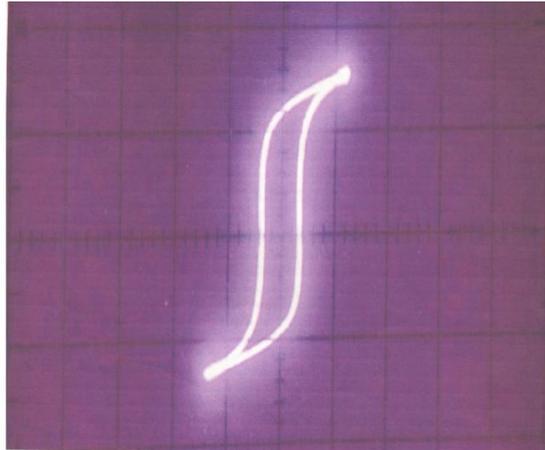


Figure 8: B-H curve obtained in the display with increasing in the input voltage
The transformer core may be replaced by a ferrite ring.

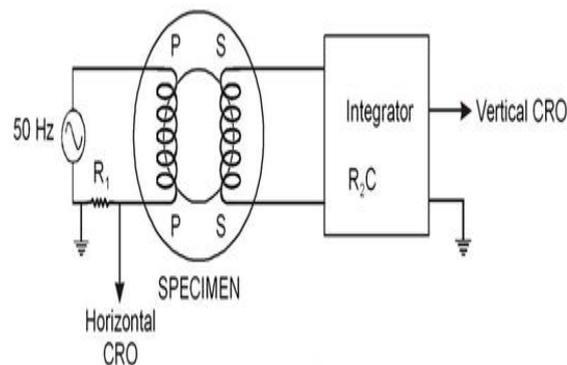


Figure 9: Ferrite ring

One patch cord and two BNC-BNC leads are supplied with the kit. The value of R1 can be selected by connecting terminal D to A or B or C (A-D = 5 ohm; B-D = 15 ohm; CD = 50 ohm) Note: The extra loops in case of Ferrites are due to the phase shift introduced, as we are working at low frequency

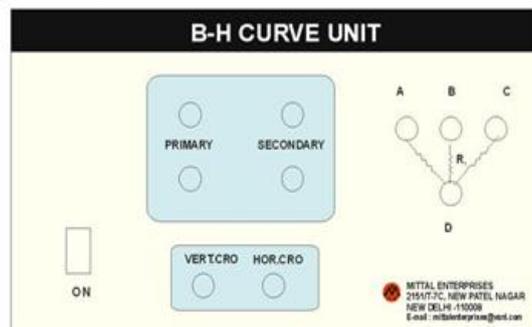


Figure 10: Front Panel of B-H Curve Unit

IV. DETERMINATION OF THE ENERGY LOSS IN THE TRANSFORMER CORE

- Connect D to A. Connect the primary & secondary terminals of the transformer specimen to respective terminals. (Following same colour coding).
- Adjust the C.R.O. to work on X-Y mode
- Connect terminal HOR .CRO to the Horizontal input of the CRO. Connect terminal VERT. CRO to the vertical input of the CRO. Switch ON the power supply of the unit. The Hysteresis loop is formed.
- Adjust the horizontal and vertical gains such that the loop occupies maximum area on the screen of the CRO. Once this adjustment is made, do not disturb the gain controls.
- Trace the loop on a translucent graph paper. Estimate the area of the loop.

- f. Note the vertical sensitivity (S_v) and horizontal sensitivity (S_H) of the C.R.O.
 g. The energy loss is given by

$$\text{Energy Loss} = \frac{N_1}{N_2} \times \frac{R_2}{R_1} \times \frac{C_2}{AL} \times S_v \times S_H \times \text{area of the loop}$$

in Joules/cycle/unit volume

Where N₁ = No. of turns in primary

N₂ = No. of turns in secondary

R₂ = 4.7KΩ R₁ = Resistance between terminals D-A, B, C

C₂ = 4.7μf

A = Area of cross-section of Specimen

L = Length of Specimen

$$\text{Energy Loss} = \frac{N_1}{N_2} \times \frac{R_2}{R_1} \times \frac{C_2 \times S_v \times S_H \times \text{Area of loop}}{\text{length} \times \text{area of cross section}} \pi \tau^2 \quad (8)$$

Where

N₁, N₂ = No. of primary and secondary turns

R₂, R₁ = Resistance connected in secondary and primary side respectively in ohms

S_v, S_H = horizontal and vertical sensitivity of the CRO in V/div.

C₂ = capacitance in farads

$$\text{Energy Loss} = \frac{1200}{1200} \times \frac{5}{25} \times 0.22 \times 10^{-6} \times \frac{0.1 \times 0.1 \times 7 \times 10^{-4}}{88 \times 10^{-2} \times (1.6 \times 10^{-4})}$$

= 1.2 mill: watts.

V. KIT DIAGRAM



Figure 11: kit diagram

VI. DRAWBACKS AND FUTURE SCOPE

6.1 DRAWBACK : The following are the major drawbacks of this project: Construction of Epstein frame for every magnetic sample that is to be tested would be a tedious job. Here, we don't consider the rotational iron losses for the magnetic material.

6.2 FUTURE SCOPE : This project can be improved by considering the aspects stated below. Improvisations in the frame should be made such that a single magnetic sheet can be tested. The impact of rotational iron losses should be taken into consideration. Other magnetic materials having different grades and thickness must be studied.

VII. CONCLUSION

This project proposes a simple and economic method for determining the iron losses of magnetic material of known composition, by constructing and Epstein frame. Through this project the designers can improve the performance of the electrical machines by predicting the iron losses and magnetic characteristics of the material. Therefore by constructing Epstein frame for different magnetic materials and determining the iron losses in a similar fashion, we can compare and determine the best suited magnetic material for the construction of transformer core.

REFERENCES

- [1]. Theory and performance of electrical machines, J.B.Guptha. https://en.wikipedia.org/wiki/epstein_frame.
- [2]. M. S. Lancarotte, A. d. A. Penteado Jr., and São Paulo, "Prediction of magnetic losses under sinusoidal or nonsinusoidal induction by analysis of magnetization rate," *IEEE Trans. Energy Convers.*, vol. 16, no. 2, pp.174–179, Jun. 2001.
- [3]. M. Amar and R. Kaczmarek, "A general formula for prediction of iron losses under nonsinusoidal voltage waveform," *IEEE Trans. Magn.*, vol.31, no. 5, pp. 2504–2509, Sep. 1995.
- [4]. P. Materu and R. Krishnan, "Estimation of switched reluctance motor losses," in *Proc. Conf. Rec. IEEE Ind. Appl. Soc. Annu. Meeting*, vol. 1, Oct. 2–7, 1988, pp. 79–90.

- [5]. T. J. E. Miller, *Switched Reluctance Motors and Their Control*. London, U.K.: Oxford Univ. Press, 1993.
- [6]. J. Faiz and M. B. B. Sharafin, "Core losses estimation in a multiple teeth per stator pole switched reluctance motor," *IEEE Trans. Magn.*, vol. 30, no. 2, pp. 189–195, Mar. 1994.
- [7]. Zhigang Zhao, Fugui Liu, Zhiguang Cheng, Weilli Yan, Lanrong Liu, Junjie Zhang and Yana Fan, "Measurement and Calculation of Core – Based B-H Curve and Magnetizing Current in DC – Biased Transformers," *IEEE Trans. Applied Superconductivity*, Vol.20, NO.3, Jun. 2010.
- [8]. John B. Goodenough, "Summary of Losses in Magnetic Materials," *IEEE Trans. Magnetics*, VOL. 38, NO.5, Sep.2002
- [9]. Ali M. Nikenejad, Robert G. Meyer, "Analysis of Eddy- Current Losses Over Conductive Substrates with Applications to Monolithic Inductors and Transformers," *IEEE Trans. Micro Wave Theory and Techniques*, Vol.49, NO.1, Jan. 2001.
- [10]. Aldo Boglietti, Andrea Cavagnino, Mario Lazzari, and Michele Pastorelli, "Predicting Iron Losses in Soft Magnetic Materials With Arbitrary Voltage Supply: An Engineering Approach," *IEEE Trans. Magnetics*. Vol.39, NO.2, Mar. 2003.
- [11]. Kapi Venkatachalam, Charles R. Sullivan, Tarek Abdallah, and Hernan Tacca, "Accurate Prediction of Ferrite Core Losses with Nonsinusoidal Waveforms Using Only Steinmetz Parameters," *IEEE Trans.* 0-7803-7554-8/02, 2002.
- [12]. Simon Steentjes, Georg von Pflingsten, Macro Hombitzer, and Kay Hameyer, "Iron-Loss Model With Consideration of Minor Loops Applied to FE-Simulations of Electrical Machines," *IEEE Trans. Magnetics*, Vol. 49, NO.7, Jul. 2013.
- [13]. Yu Zhang, "Magnetic Characteristics and Core Losses in Machine Laminations: High –Frequency Loss Prediction From Low-Frequency Measurements," *IEEE. Trans. Industry Apps*. VOL.48, NO.2, Mar/Apr. 2012.
- [14]. Maged Ibrahim, Pragesen Pillay, "Novel Equipment for the Measurement of Core Losses in Laminations for Advanced Machines," *IEEE IEMDC- 2011*, 978-1-4577-0061-3/11
- [15]. Mariusz Najgebauer, "Models for Predictions of Energy Loss in Soft Magnetic Materials," XII International PhD Workshop OWD 2010, 23-26 Oct. 2010.
- [16]. Marion L. Hodgson, "Mathematical Theory and Calculations of Magnetic Hysteresis Curves," *IEEE Trans. On Magnetics*, Vol.24, NO.6, Nov. 1988
- [17]. Francisco de Leon, Adam Semlyen, "A Simple Representation of Dynamic Hysteresis Losses in Power Transformers," *IEEE Trans. Power Delivery*. Vol. 10, No.1, Jan.1995
- [18]. Ewald F. Fuchs, Deniz Yildirim, W. Mack Grady, "Measurement of Eddy – Current Loss Coefficient P_{EC-R} , Derating of single-Phase Transformers, and Comparison with K-Factor Approach. *IEEE Trans. Power Delivery*. Vol. 15, No.1, Jan 2000.
- [19]. Dan M. Ionel, Mircea Popescu, Stephen J. Dellinger, T.J.E Miller, Robert J. Heidman, and Malcolm I. McGilp, "On the Variation With Flux and Frequency of the Core Loss Coefficients in Electrical Machines," *IEEE Trans. Industry Apps*. Vol-42, No.3, May/June 2006.
- [20]. J. Reinert, A. Brockmeyer, R.W. De Doncker, "Calculation of Losses in Ferro- and Ferrimagnetic Materials Based on the Modified Steinmetz Equation," *IEEE*. 0-7803-5589-X/99, 1999.