

Calculation of Local Iron Loss in Electrical Machines Using Finite Elements Method

Ahmad Darabi, Mohammad Ebrahim Ghazi, Hamid Lesani, and Ahmad Askarinejad

Abstract—Calculations of iron losses in the electrical machines are normally based on experimental characteristics of core material used in the machines. These methods with simplified machine analysis approximations are usually employed for calculation of total iron losses of electrical machines whilst local flux densities and corresponding local iron losses especially when designing of the machine and its cooling system are most important. In this paper, a Finite Element based simulation coupled with well known hysteresis model called Preisach model is used to calculate local iron loss of a synchronous machine. Calculation of iron loss particularly local loss with some accuracy, offers this opportunity to the designer such as to reduce losses where loss densities are high. This also leads to an optimum design of ventilation and cooling system.

Index Terms— Electrical Machine, Iron Loss, Hysteresis, Finite Elements, Preisach Model.

I. INTRODUCTION

A substantial portion of the losses in electrical machines is loss in the iron core including hysteresis loss, eddy current loss and stray loss. Most parts of the electrical machines, except parts of the machine which are made by permanent magnet, are material with high permeability and low coercive force and conductivity. Ferrosilicon sheets with small eddy current losses own high permeability, low coercive force and less hysteresis losses, so they have most application in fabrication of electrical machines [1].

Since the eddy current loss is relatively small in the iron sheets, this loss are usually combined with hysteresis loss by a minor increase in the area of the hysteresis loops. The sum of eddy and hysteresis losses in the unit weight of silicon sheets when subjected to a one-dimension (1D) sinusoidal field is usually calculated using experimental and semi-experimental equations, tables and curves in term of maximum scalar flux

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density of the core. This experimental data is available for a particular frequency then the result of calculation should be modified by especial factors and method for other frequencies.

Because of the complicated structures, various operating conditions of the electrical machines and also non-linear, multi-values magnetic characteristics of the iron, the flux densities of different points in the machine are not usually pure sinusoidal waveforms. Rotational losses, losses due to the flux harmonics and other core losses except eddy and hysteresis losses of the first harmonic, are called stray losses. These losses are changed widely for different machines and various operating conditions [2]. Precise calculation of stray losses of electrical machines is a complicated issue and they are estimated by use of methods which are normally based on experiments. Evaluation of local losses and therefore total core losses in design stage of an electrical machine is much important. This helps the designer to modify the parts of the machine where have higher losses and so reduces the total loss most efficiently. This can also be used for optimum cost-effective design of ventilation and cooling system.

Hysteresis is a complicated and interesting phenomenon not only in magnetic behaviour of materials but also in various branches of science and engineering. Static and dynamic hysteresis has been modelled for 1D, 2D and 3D fields. The Jiles-Atherton model is a physical model for ferromagnetic hysteresis based on the energy balance exposed in a magnetic material [3]. In this model, the energy given to the magnetic material is equal to the sum of magnetic stored energy and the loss of energy by domains wall movement to overcome microscopic defects which causes hysteresis losses. The other interesting model of hysteresis is Preisach model which has been suggested by F. Preisach at 1935. This model displays a full mathematical description of hysteresis [4].

In this paper, a synchronous alternator is modelled using SLIM Finite Element (FE) software [5]. For a given operating condition of the machine, magnetic fields of any point can be calculated using FE simulation. The FE software employs single value magnetization curve of iron so it cannot directly calculate hysteresis loss. In this paper, the field analysis results obtained by FE simulation are used with static scalar Preisach model and iron losses are determined for each point of the stator or rotor core. The reason for 1D magnetic field assumption is that magnetic fields in the most parts of rotor core and stator teeth of a synchronous alternator are almost radial and in the stator yoke are normally circumferential. In this FE simulation coupled with Preisach model, magnetic field

harmonics and minor loops are also taken into account. Optimum values of the parameters used in the Preisach density function, are calculated by a simulation using experimental data available for the ferromagnetic material of the stator core. The electrical machine studied in this paper, is a 31.5 KVA brushless synchronous generator with a diesel engine prime mover manufactured by Lerroy Somer Ltd [6]. Local iron loss is calculated in the centre of a stator tooth as a typical point by FE coupled scalar Preisach model.

II. PREISACH MODEL

Preisach modelling has been developed in both scalar and vector forms for definition of transient and steady-state hysteresis phenomena [4]. In the 1D static Preisach modelling, magnetization (M) of a homogenous ferromagnetic material in a steady-state ac sinusoidal and non-sinusoidal magnetic field can be calculated by superimpose of simple hysteresis loops. This hysteresis loop is a simple delay component ($\hat{\gamma}_{ab}$) shown in figure 1. The relation between input variable $u(t)$ and output variable e.g. $f(t)$ at time t can be described as follow:

$$\begin{aligned} f(t) &= 1 && \text{if } u(t) \geq a \\ f(t) &= -1 && \text{if } u(t) \leq b \\ f(t) &= \text{unchanged} && \text{if } b < u(t) < a \end{aligned} \tag{1}$$

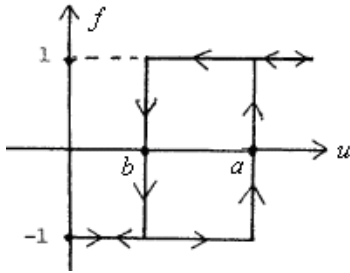


Fig. 1. Delay component

Let us consider operator $\hat{\gamma}_{ab}$ which acts on input $H(t)$ and gives output $M(t)$. If for an arbitrary point in the magnetic material we suppose there is infinite number of these relays with corresponding operators, the output of these set will be as:

$$M(t) = \iint_{a \geq b} p(a,b) \hat{\gamma}_{ab}(H(t)) da db \tag{2}$$

Where $p(a,b)$ can be called density function.

Preisach operator has a local memory with a dominant maximum and minimum. For a homogenous magnetic material, the value of the minimum is minus of the maximum say H_s . Therefore if $b < -H_s$ or $a > H_s$, then $p(a,b) = 0$, so Preisach plane as shown by a triangle in figure 2 is defined as:

$$S^\Delta = \{(a,b) \mid a \geq b, b \geq -H_s, a \leq H_s\} \tag{3}$$

For any point $(a,b) \in S$, there is a corresponding operator $\hat{\gamma}_{ab}$ and for instant t the plane S is divided into two sections as follow:

$$\begin{aligned} S^+(t) &= \{(a,b) \in S \mid \text{output of } \hat{\gamma}_{ab} \text{ at } t \text{ is } +1\} \\ S^-(t) &= \{(a,b) \in S \mid \text{output of } \hat{\gamma}_{ab} \text{ at } t \text{ is } -1\} \end{aligned} \tag{4}$$

Where at time t , $S(t) = S^+(t) \cup S^-(t)$ and equation 2 can be written as:

$$M(t) = \iint_{S^+(t)} p(a,b) da db - \iint_{S^-(t)} p(a,b) da db \tag{5}$$

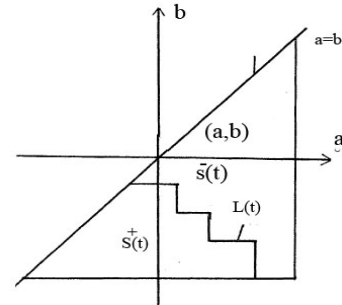


Fig. 2. Preisach triangle

For any instant t the Preisach plane is divided into the region with upper switching field $S^+(t)$ and the region with lower switching field $S^-(t)$. When the input $H(t)$ increases, a vertical line sweeps the Preisach plane from left to right and when $H(t)$ decreases, a horizontal line sweeps downwards. If $H(t)$ is alternating between two absolute extrema H_s and $-H_s$ with a limited number of local extrema, obviously $M(t)$ will vary alternatively between two absolute extrema such as M_s and $-M_s$. Therefore it can be simply proved that density function should satisfy equation given by:

$$\iint_{S(t)} p(a,b) da db = M_s \tag{6}$$

Consequently equation 5 can be written as:

$$M(t) = -M_s + 2 \iint_{S^+(t)} p(a,b) da db \tag{7}$$

Once $M(t)$ is obtained, values of $B(t)$ can be evaluated by:

$$B(t) = \mu_0 \{H(t) + M(t)\} \tag{8}$$

Where $\mu_0 = 4\pi \cdot 10^{-7}$

III. COMPUTER SIMULATION OF PREISACH MODEL

Magnetization or flux density of steady-state-state and then hysteresis losses of a ferromagnetic core can be calculated

using static 1D Preisach model, when the core material is subjected to a symmetrical alternating field with negative and positive peaks. The magnetic field do not need to be sinusoidal. In fact the number of broken lines shown in figure 2 at boundary of $S^+(t)$ and $S^-(t)$, illustrates the number of local extrema of magnetic field from last absolute extrema until present time t . In this computer simulation, once the vertices of broken lines are updated for the present time t , then $M(t)$ and $B(t)$ are evaluated one after the other using Equation 7 and Equation 8 respectively. With respect to the value of $H(t + \delta t)$ which is bigger or smaller than $H(t)$, the new vertices of boundary of two areas are determined for the time $t + \delta t$. The important point in this stage is that if δt is chosen small enough, the variation of $H(t)$ will be also very small and therefore the number of new vertices will be maximum one unit different from the previous one. This will considerably simplify computer programming and data storing.

IV. DENSITY FUNCTION AND ITS OPTIMUM PARAMETERS

The density function $p(a, b)$ can be calculated using the first order inverse curve for any magnetic material. A common density functions which have been used to model the hysteresis is a Gaussian form [4] as:

$$2p(a, b) = \frac{m_{ss}}{\pi\sigma_1\sigma_2} \exp\left(-\frac{(a+b)^2}{4\sigma_1^2} - \frac{(a-b-2u_c)^2}{4\sigma_2^2}\right) \tag{9}$$

This particular density function with four adjustable parameters is employed in this paper. It is clear that four parameters of this function, m_{ss} , σ_1 , σ_2 and u_c should be adjusted suitably for different parts of Preisach triangle (figure 2) to minimise diversity between the resultant $B(t)$ obtained

by Preisach model with those of the experimental $B(t)$ for any alternating magnetic field $H(t)$. For ferromagnetic material used in electrical machine usually the only available data are magnetization and loss curves in term of peak values of the sinusoidal flux density. Fortunately these are the important necessary information for the objective of this paper. But a density function with constant parameters does not usually provide a good approximation of hysteresis in Preisach model for a wide range operating conditions of the magnetic material used as a core of an electrical machine. So total region of Preisach triangle is divided into a number of smaller regions and then the optimum parameters are calculated for any region. A discrete set of peak values of the magnetic field intensity, flux density and corresponding areas of the hysteresis loops are available for a material named LOSIL-630 used in the synchronous generator. This set is used in an optimisation program and optimum parameters of density function are calculated. Optimization program executes a Matlab toolbox called "fminunc". This program runs computerised Preisach model for sinusoidal inputs, and adjusts the parameters of the density function commencing with an initial guessed values such as to minimize relative error between calculated and measured peak values of the flux density and areas of hysteresis loops. The resultant optimum parameters of density function of LOSIL-630 for different regions are given in table I. A few calculated hysteresis loops and measured magnetic curve are shown in figure 3. Experimental area of hysteresis loops obtained from loss curves and those of calculated values by Preisach model with optimum parameters are given in table 2 for comparison. Figure 3 and table II shows a good agreement between these values and illustrate the accuracy and magnificence of such optimum density function and Preisach model. Obviously if density function given by Equation 9 does not give a good approximation for a hysteresis of a material, other form of density function has to be examined.

TABLE I
Optimum parameters of density function for Losil-630

section	a and b values	$10^{-4}m_{ss}$	σ_1	σ_2	u_c
1	$-100 < b \leq -100 < a < 100$	74.49167	70.23533	67.95768	80.960259
2	except section no. 1 $-112 < b \leq -112 < a < 112$	73.50453	43.63087	60.24348	83.67477
3	except sections with no. less than 3 $-122 < b \leq -122 < a < 122$	88.91253	69.66376	46.45285	80.73351
4	except sections with no. less than 4 $-132 < b \leq -132 < a < 132$	91.89059	64.69753	42.70985	89.04827
5	except sections with no. less than 5 $-142 < b \leq -142 < a < 142$	80.90639	35.17563	52.05150	105.68034
6	except sections with no. less than 6 $-154 < b \leq -154 < a < 154$	78.92915	06.87975	66.51201	108.94130
7	except sections with no. less than 7 $-168 < b \leq -168 < a < 168$	86.45607	53.81372	61.29249	118.1189
8	except sections with no. less than 8 $-188 < b \leq -188 < a < 188$	79.55638	57.66232	32.03302	109.73872
9	except sections with no. less than 9 $-216 < b \leq -216 < a < 216$	68.13034	32.47861	63.97896	117.00194
10	except sections with no. less than 10 $-266 < b \leq -266 < a < 266$	75.53657	43.29980	82.04428	132.48656
11	except sections with no. less than 11 $-346 < b \leq -346 < a < 346$	117.96477	105.06149	64.73821	111.74766
12	except sections with no. less than 12 $-500 < b \leq -500 < a < 500$	115.02649	98.38718	119.95690	143.26790
13	except sections with no. less than 13 $-880 < b \leq -880 < a < 880$	165.39782	251.85881	78.83422	131.25544
14	except sections with no. 1 to 13	259.73531	421.63571	129.47513	215.13744

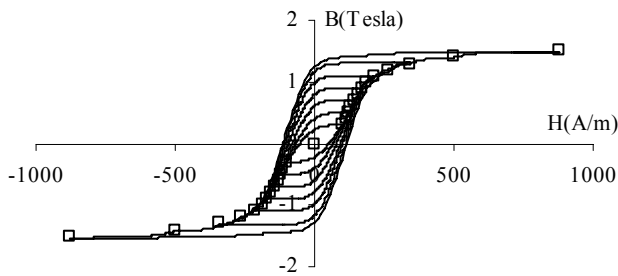


Fig. 3. A few calculated hysteresis loops (—) and experimental magnetizing curve (□)

TABLE II

Experimental and calculated values of hysteresis area of Losil-630 for sinusoid field

Peak values of flux density in Tesla	Experimental values of hysteresis area in A. Tesla/m	Calculated values of hysteresis area in A. Tesla/m
0	0	0
0.3	54.24	55.3381
0.4	86.8	86.9625
0.5	120.9	120.9619
0.6	159.65	163.3157
0.7	205.37	208.6779
0.8	252.65	251.6351
0.9	310	313.4634
1	372	372.8282
1.1	443.3	425.665
1.2	520.8	525.714
1.3	589	589.2113
1.4	697.5	688.8814

V. FE MODEL AND MAGNETIC FIELD CALCULATION

Finite element method and its software are well known as an efficient tool for magnetic field analysis. To calculate time dependent magnetic field for any point of the machine, firstly the structure and elements of machine must be known fully.

Current of each coil must be known instantaneously as the inputs of the FE software. These currents can be calculated or measured. The FE software might be employed to calculate currents using directly time-stepping method or indirect parametric model.

In this paper the self and mutual inductances of the machine versus rotor position are calculated using 2D FE SLIM [5]. These parameters are applied to another computer simulation and the currents of all coils are determined for any balance and unbalance load operating condition of the generator [7]. FE analysis of the machine is performed again using these currents as inputs for calculation of magnetic field intensity for any required point of the stator or rotor core. A scalar Preisach model will be used for iron loss evaluation. So at this stage it would be necessary to calculate radial components of the magnetic field intensity in the stator teeth or circumferential

components in the stator yoke as dominant components in these sections of the machine. The calculated magnetic field intensity in the centre of a stator tooth for nominal operation of generator is shown in figure 4. The Fourier series of this waveform is used as an input for computerised Preisach model.

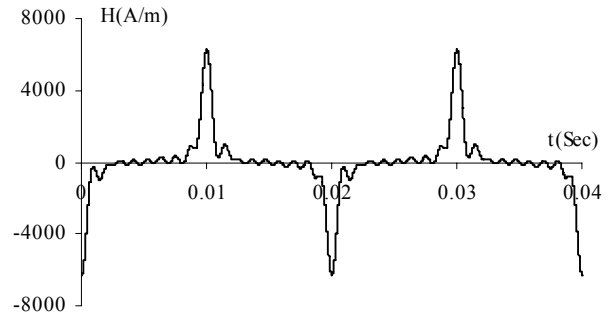


Fig. 4. Calculated magnetic field intensity in a stator tooth

VI. FLUX AND LOCAL LOSS CALCULATION BY PREISACH MODEL

Calculated magnetic field by FE software in any point of the machine can be used as an input for Preisach model simulation to calculate magnetization $M(t)$ and the flux density $B(t)$ of that point. By use of magnetic field intensity given by figure 4 as an example, the flux density waveform and B-H loop for the centre of that stator tooth as shown respectively in figures 5 and 6 are obtained by 1D Preisach model simulation.

Using $H(t)$ and $B(t)$ wave form, weight density of the magnetic material $\rho_m = 7750 \text{ kg} / \text{m}^3$ and frequency $f = 50$, the iron loss per unit weight P_c can be calculated for any point of machine by:

$$P_c = \frac{f}{\rho_m} \oint H dB = \frac{f}{\rho_m} \int_0^1 H(t) \frac{dB}{dt} dt = W_h f / \rho_m \text{ w/kg} \tag{10}$$

Where W_h is the area of the B-H curve in one cycle.

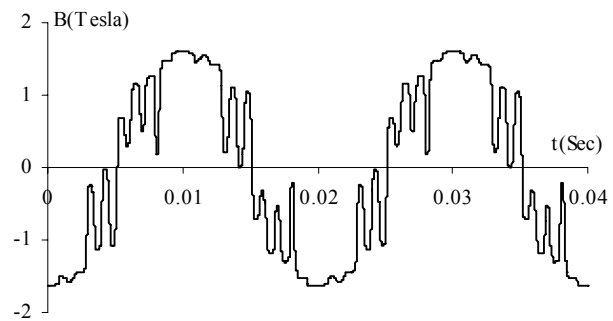


Fig. 5. Calculated flux density in the centre of stator tooth

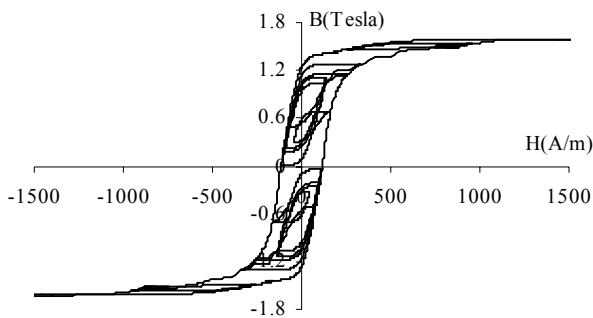


Fig. 6. Calculated B-H curve in the centre of stator tooth

Using Preisach model and equation 10 the resultant area of the B-H curve for one cycle and calculated iron loss for the tooth centre mentioned above are $1949.019655 \text{ A.Tesla/m}$ and 12.5743 w/kg respectively. While if the peak value of the flux density is used with experimental sinusoid characteristic, the iron loss would be 6.2 w/kg which is far from the values obtained by this simulation taking all harmonics into account. If only the peak value of the first harmonic flux density is applied with experimental characteristic, then the loss will be 5.95 w/kg which this value is most inaccurate. These results show accuracy of the FE coupled Preisach modelling for iron loss calculations comparing with old method.

In the static Preisach model coupled with FE, the transient iron loss and also rotational fluxes are neglected. In normal operating conditions of the generator, ignoring the circumferential fluxes in the stator teeth and rotor core and radial fluxes in stator yoke generally is not far from the fact. But this simplification can not be applied for many electromagnetic system and electrical machines in particular condition. For these applications, multi-dimensional Preisach model might be used [4]. Usually, iron losses in transient operation of the machine due to its short duration of time are not very important. For any exception and particular case one can use dynamic PM.

VII. CONCLUSION

In this paper, optimum parameters of Preisach model are calculated using experimental data available for a ferromagnetic material used in electrical machines. Magnetization and iron losses obtained from this simulation for sinusoidal fields are well in agreement with experimental results. In this paper also a synchronous generator is simulated by finite element software. Then magnetic field harmonics in the centre of a stator tooth as a typical point is evaluated under normal operating condition. Using the resultant magnetic field and applying Preisach model, magnetic flux density and local iron loss are calculated for the centre of the stator tooth. The results of this simulation are compared with the results obtained by the experimental characteristics of the ferromagnetic material in which the harmonics are neglected. The simulation

shows the capability of Preisach model coupled with Finite Elements in prediction of the flux waveform and iron loss more precisely in comparison with common experimental method used for iron loss calculation.

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