Abstract: A numerical method for the evaluation of magnetic iron losses in steel laminations used in electrical machines is described. The magnetodynamic model for the magnetic field strength \( H \), derived from the Maxwell equations, is coupled with the Preisach theory, describing the hysteresis behaviour. The resulting highly nonlinear and transient boundary value problem for \( H \) is solved numerically by a modified finite-element, finite-difference method. The identification of the material parameters, for which the authors invoke the Everett theory, is discussed in detail. The model is validated by the comparison of numerical experiments and measurements for the \( B-H \) loops. For the material considered the rate-dependent Preisach model is found to be more reliable than the classical Preisach model.

1 Introduction

Core losses are very important for the efficiency of a rotating electrical machine and depend on the design of the motor. As the magnetic flux is highly distorted in many regions of the machine cores, classical characterisation techniques seem to be insufficient to describe the electromagnetic behaviour of the nonoriented electrical steel in detail. Therefore new characterisation techniques have to be developed. Such new techniques are discussed in this paper. The computation of electromagnetic fields inside ferromagnetic laminations of electrical machines requires an accurate description of the hysteresis and eddy-current effects when considering arbitrary excitation waveforms. The evaluation presented of the electromagnetic losses in electrical machines relies on the computation of the electromagnetic fields inside the laminations. In [1] a modified finite-element (FE), finite-difference (FD) method is presented in which the well-established classical Preisach hysteresis model (CPM) is embedded in magnetodynamic field calculations for one lamination. The numerical results for the magnetic losses, obtained for the materials considered in [1], are in good agreement with the experimental values. However, for other materials a systematic discrepancy has been observed. Actually the frequency dependence of the hysteresis effects may have a large influence on the magnetic behaviour of the material as pointed out in [2] for example. Therefore a rate-dependent Preisach model (RPM), recently introduced by Bertotti [3], has been incorporated in magnetodynamic field calculations, briefly reported in [4]. Thus, in this recent model the magnetic behaviour of the Preisach dipoles is rate-dependent. We recall that in the Preisach theory a ferromagnetic material is modelled as to be composed of elementary dipoles, see [5-7] for a more recent account. These Preisach dipoles are mathematical concepts and should not be considered as atomic dipoles, although recently a physical interpretation has been sought [8]. In the CPM these dipoles switch instantaneously, while in the RPM they are assumed to switch at a finite rate. The most important consequence of this improvement is the enlargement of the hysteresis loops with increasing frequency. This effect allows the modelling of the extra dynamic losses appearing at increasing frequency. These extra losses have to be added to the classical eddy-current losses and the quasistatic hysteresis losses to give the total electromagnetic losses, see [8] for example.

The magnetic behaviour of the material, as described by the RPM, may be incorporated into the magnetodynamic model in a direct and correct manner. The coupling of this magnetodynamic model with other valuable hysteresis models that have been reported in the literature [9, 10], turns out to be more cumbersome for the study presented.

2 Mathematical model

2.1 Classical Preisach model against rate-dependent Preisach model

2.1.1 Behaviour of elementary Preisach dipole: The elementary dipoles, comprising the ferromagnetic material, are characterised by the values of the switching fields \( \alpha \) and \( \beta \) \((\alpha \geq \beta)\), Fig. 1 (dashed line). In the CPM the magnetisation \( M_d \) of the dipole only takes the value \( +1 \) or \(-1\). Explicitly,

\[
M_d = \begin{cases} 
+1 & : H(t) > \alpha \text{ or } (\beta < H < \alpha \text{ and } H_{last} > \alpha) \\
-1 & : H(t) < \beta \text{ or } (\beta < H < \alpha \text{ and } H_{last} < \beta) 
\end{cases}
\]
Here $H_{last}$ is the last extreme value kept in memory outside the interval $[\beta, \alpha]$. Thus the CPM is rate-independent.

![Figure 1: $(M_d, H)$-characteristics of Preisach dipole](image)

In the RPM of [3] the dipoles are assumed to switch at a finite rate, proportional to the difference between the local magnetic field $H(t)$ and the elementary loop switching fields $\alpha$ and $\beta$. The factor of proportionality, denoted by $k$, is an extra material parameter. Explicitly the evolution in time of the magnetisation $M_d$ is given by

$$\frac{dM_d}{dt} = \begin{cases} k(H(t) - \alpha) & H(t) > \alpha \text{ and } M_d < +1 \\ k(H(t) - \beta) & H(t) < \beta \text{ and } M_d > -1 \\ 0 & \text{in the other cases} \end{cases}$$

When the material is demagnetised, the magnetisation of the dipoles is chosen as follows:

$$\begin{cases} M_d = -1 & \alpha + \beta > 0 \\ M_d = +1 & \alpha + \beta < 0 \end{cases}$$

To illustrate the difference in behaviour of the classical Preisach dipole and the rate-dependent Preisach dipole, consider the dipole with switching fields $\alpha_1$ and $\beta_1$ equal to 100 and 50 A/m, respectively. As an example, a sinusoidal field variation $H = 150 \sin 2\pi ft$ is applied. The more complex $(M_d, H)$-characteristics for the dipole $(\alpha_1, \beta_1)$ are shown in Fig. 1 (dotted and full line) when using the RPM. They result from the switching of the Preisach dipole at a finite rate as described by eqn. 2. Notice that the magnetisation of the dipole $M_d$ may vary in time in an asymmetric way (offset) (see dotted line in Fig. 1). Such an asymmetry will not occur for the $B-H$ relation, resulting from the Preisach model, owing to a compensation mechanism by other Preisach dipoles (see for instance the dipole with parameters $\alpha_2, \beta_2$).

2.1.2 Material characterisation: The relative density of the Preisach dipoles is represented by the distribution function $P(\alpha, \beta)$, cf. [5, 6]. Correspondingly, the induction $B(H(t), H_{past}(t))$ takes on the following form in the Preisach model:

$$B(H(t), H_{past}(t)) = \frac{1}{2} \int_{-H_m}^{H_m} d\alpha \int_{-H_m}^{H_m} d\beta \eta(\alpha, \beta, t) P(\alpha, \beta)$$

Here $P(\alpha, \beta)$ is assumed to be negligibly small when either $\alpha > H_m$ or $\beta < -H_m$, where $H_m$ is directly obtained from the experimental evaluation of $P$. Moreover $\eta(\alpha, \beta, t)$ is the value at the time $t$ of the magnetisation $M_d$ for the dipole with the parameters $\alpha$ and $\beta$. Of course, this results in the induction $B$ to depend on the magnetic field $H(t)$ and its history $H_{past}(t)$.

To illustrate the difference between the CPM and the RPM in a theoretical way, consider the variation of the magnetic field $H$ as shown in Fig. 2 for a chosen time interval $[0, t_0]$. The two models are compared on two levels: the function $\eta$ in the $(\alpha, \beta)$-plane and the $B-H$ relation obtained by eqn. 4.

As mentioned, in the CPM, $\eta(\alpha, \beta, t)$ only takes the values $+1$ or $-1$. The region $(-H_m < \alpha < H_m, -H_m < \beta < \alpha)$ is divided into two subregions $S^+$ and $S^-$ where $\eta(\alpha, \beta, t)$ equals $+1$ and $-1$, respectively. The interface between $S^+$ and $S^-$ is determined by $H(t)$ and $H_{past}(t)$, as described in detail in [7]. Fig. 3 shows the function $\eta$ at time point $t = t_0$. For the CPM, eqn. 4 becomes

$$B(H(t), H_{past}(t)) = \frac{1}{2} \int_{S^+} d\alpha d\beta P(\alpha, \beta) - \frac{1}{2} \int_{S^-} d\alpha d\beta P(\alpha, \beta)$$

More generally, when the field strength $H$ changes monotonically in time, the variation of induction $B$ in absolute value is given by

$$\Delta B(H(t), H_{past}(t)) = \int_{D_+} d\alpha d\beta P(\alpha, \beta)$$
where $D_1$ is the region in the $(\alpha, \beta)$-plane in which the dipoles switch from one polarisation to the opposite one.

In the RPM however, $\eta(\alpha, \beta, t)$ varies (at each fixed time $t$) within the whole range from $-1$ to $+1$ according to eqn. 2. Now the function $\eta$ can be visualised for each time point in the $(\alpha, \beta)$-plane using $\eta$ isolines. Fig. 3 shows the $\eta$ isolines for time point $t = t_0$. Finally, using eqn. 4, we obtain for the RPM the $B$-$H$ relation shown in full line in Fig. 4, while the CPM results in the $B$-$H$ relation in dashed line. These $B$-$H$ relations correspond to the time interval $[0, t_0]$ in Fig. 2.

\begin{align}
\frac{1}{\sigma} \frac{\partial^2 H}{\partial x^2} &= \frac{\partial B}{\partial t}
\end{align}

where $B$ is the magnitude of the magnetic induction $\vec{B} = B(x) \vec{e}_z$, while $\sigma$ is the electrical conductivity of the material. Due to this conductivity eddy currents $\vec{J}$ are generated in the material. In view of the magnetodynamic model, $\partial B/\partial t$ must be related to the magnetic field $H(t)$, both for the CPM and for the RPM. In the former case one simply has, cf. [1],

\begin{align}
\frac{1}{\sigma} \frac{\partial^2 H}{\partial x^2} &= \mu_0 (H(x, t), H_{past}(x, t)) \frac{\partial H}{\partial t}
\end{align}

with

\begin{align}
k_1(H(x, t), H_{past}(x, t)) &= \frac{k}{D_1(x, t)} \int P(\alpha, \beta) d\alpha d\beta \\
&+ \frac{k}{D_2(x, t)} \int P(\alpha, \beta) d\alpha d\beta
\end{align}

and

\begin{align}
k_2(H(x, t), H_{past}(x, t)) &= \frac{k}{2} \int \alpha \cdot P(\alpha, \beta) d\alpha d\beta \\
&+ \frac{k}{2} \int \beta \cdot P(\alpha, \beta) d\alpha d\beta
\end{align}

Herein $\mu_0$ is the reversible differential permeability of the magnetic material. In the RPM however, eqns. 4 and 7 combined with eqn. 2, written out for $\eta(\alpha, \beta, t)$, leads to

\begin{align}
\frac{1}{\sigma} \frac{\partial^2 H}{\partial x^2} &= \mu_0 (H(x, t), H_{past}(x, t)) \frac{\partial H}{\partial t}
\end{align}

with

\begin{align}
k_1(H(x, t), H_{past}(x, t)) &= \frac{k}{D_1(x, t)} \int P(\alpha, \beta) d\alpha d\beta \\
&+ \frac{k}{D_2(x, t)} \int P(\alpha, \beta) d\alpha d\beta
\end{align}

and

\begin{align}
k_2(H(x, t), H_{past}(x, t)) &= \frac{k}{2} \int \alpha \cdot P(\alpha, \beta) d\alpha d\beta \\
&+ \frac{k}{2} \int \beta \cdot P(\alpha, \beta) d\alpha d\beta
\end{align}

Herein $\mu_0$ is the reversible differential permeability. $D_1$ and $D_2$ are the domains in the Preisach plane representing dipoles in an intermediate state, switching to positive and negative saturation, respectively. Of course, the time and space dependency of $D_1$ and $D_2$ is through the local magnetic field $H(x, t)$ and its history $H_{past}(x, t)$.

To obtain a well-posed boundary value problem, eqns. 1, 8 and eqns. 2, 9 must be completed with the suitable boundary conditions (BCs) and initial conditions (ICs), viz.

\begin{align}
\frac{\partial H(x = 0, t)}{\partial x} &= 0, \quad \frac{\partial H(x = d, t)}{\partial x} = \frac{\sigma}{2} \frac{\partial \varphi}{\partial t}
\end{align}

and

\begin{align}
H(x, t = 0) &= 0, \quad \begin{cases} \eta(\alpha, \beta, t = 0) = +1 : \alpha + \beta < 0 \\
\eta(\alpha, \beta, t = 0) = -1 : \alpha + \beta > 0
\end{cases}
\end{align}

The first BC reflects the symmetry in the lamination. The second BC follows when combining eqn. 7 with the symmetry and with the definition of the flux $\varphi(t)$ through the lamination. Finally, the IC, eqn. 13, corresponds to the demagnetised state of the material.

We refer to [1, 4] for the numerical solution of the highly nonlinear parabolic problem described by eqns. 1, 8, 12 and 13 for the CPM and by eqns. 2, 9, 12 and 13 for the RPM, respectively.
3 Measuring setup

The experimental setup for the measurements of hysteresis loops and for the identification of the Preisach function is illustrated in Fig. 6. Sheets of the material under consideration have been eroded in the form of rings, all with a thickness of 2$d$ and an inner and outer diameter of $D_{in} = 90 \text{mm}$ and $D_{out} = 100 \text{mm}$ (diameter ratio of approximately 1.1). These $n$ laminations are assembled to form a stacked ring core on which an outer excitation winding ($n_1$ turns) and an inner measurement winding ($n_2$ turns) are placed. In [12] it is shown that for these dimensions the influence of the axisymmetry and the edge effects on the total iron losses are negligible. Therefore to evaluate numerically the iron losses in the ring core we may use the magnetodynamic model of the previous Section with the 1D space dependency (x-direction in Fig. 5). The actual current in and voltage over the excitation winding (high impedance measurement): 

$$e_2 = n_2 \frac{d\varphi}{dt}$$  \hspace{1cm} (14)

Finally, the control signal for the power amplifier is generated by the acquisition system.

Fig.6 Scheme of measuring setup

Two types of excitation are considered.

3.2 Enforce average magnetic induction $B_a(t)$ through lamination

By using the voltage control mode of the power amplifier we can enforce a sinusoidal flux $q(t) = n S B_a(t) = n S B_{a,\max} \cos(2\pi ft)$ in the material, considering an iterative procedure. At the $i$th iteration level, to obtain a sinusoidal flux $n S B_{ai}$ we calculate the voltage $v_i^{(i)}$ that must be enforced at the excitation winding using the current waveform of the previous iteration level, i.e. $i^{(i-1)}$. Thus we take into account properly the voltage drop over the resistance $R_i$ of the excitation winding

$$v_i^{(i)}(t) = R_i \frac{d}{dt} \left[ i^{(i-1)}(t) + n_1 S \frac{dB_a}{dt} \right]$$  \hspace{1cm} (16)

with $R^0 = 0$ and $S = (D_{out} - D_{in}) \ d$. The average magnetic induction $B_a(t)$ entering eqn. 16 is given by

$$B_a(t) = \frac{1}{S} \int_{D_{in}/2}^{D_{out}/2} \int_{-d}^{+d} B dx dz \text{~(17)}$$

On the other hand, the total electromagnetic iron losses per cycle and per unit volume reads [13]

$$E = \frac{1}{n_{lm} S} \int_{t}^{t + \frac{T}{2}} \int_{t}^{t + \frac{T}{2}} n_1 i_1(t) \frac{d\varphi}{dt} dt$$  \hspace{1cm} (18)

where $f$ is the frequency of the enforced sinusoidal flux $\varphi$. Taking into account eqn. 15 and the form of the enforced flux, this gives [14],

$$E = \int H_b dB_a$$  \hspace{1cm} (19)

This type of excitation is used in Section 4 for the experimental verification of the models of Section 3.

4 Parameter identification

In this Section we discuss the identification of the distribution function $P(\alpha, \beta)$ in the CPM and the RPM. The identification is based on the Everett theory [11].

4.1 Everett function

According to the Everett theory we introduce the function $E_v(H_1, H_2)$ by

$$\{ E_v(H_1, H_2) \equiv \int \int d\alpha d\beta P(\alpha, \beta) \text{~} H_1 \leq H_2 \}$$\hspace{1cm} \{ E_v(H_1, H_2) \equiv E_v(H_2, H_1) \text{~} H_1 > H_2 \}$$  \hspace{1cm} (20)

where $\Delta$ is the triangular area in the $(\alpha, \beta)$-plane enclosed by the lines $\alpha = \beta, \alpha = H_2$ and $\beta = H_1$. Taking into account eqn. 6, $E_v(H_1, H_2)$ gives the absolute value of the induction variation $\Delta B$ when the magnetic field changes from $H_1$ to $H_2$. Here $H_1$ is an extremum and no extrema are evaded from the memory. Due to eqn. 20 and the symmetry of $P(\alpha, \beta)$ with respect to the line $\alpha + \beta = 0$, we have

$$E_v(H_1, H_2) = E_v(H_2, H_1) = E_v(-H_1, -H_2)$$  \hspace{1cm} \{ E_v(-H_2, -H_1) \}$$  \hspace{1cm} (21)

4.2 Averaging the Everett function

For each couple $(H_1, H_2)$, where $(H_1 < H_2$ and
In the \((H_1, H_2)\)-plane we deliberately define the average Everett function \(\bar{E}_v\) as
\[
\begin{align*}
\bar{E}_v(H_1, H_2) & = \frac{1}{4} \sum_{i=1}^{4} E_v^{(i)}(H_1, H_2)  & H_1 < H_2, H_1 > -H_2 \\
\bar{E}_v(H_1, H_2) & = \bar{E}_v(H_2, H_1)  & H_2 > H_1, H_1 > -H_2 \\
\bar{E}_v(H_1, H_2) & = \bar{E}_v(-H_1, -H_2)  & H_1 > H_2, H_1 < -H_2 \\
\bar{E}_v(H_1, H_2) & = \bar{E}_v(-H_2, -H_1)  & H_1 < H_2, H_1 < -H_2
\end{align*}
\]
(23)

Apparently this function retains the property described by eqn. 21 such that \(\bar{E}_v\) can be introduced in the classical Preisach model. This function is shown in Fig. 8.

We want to estimate the error involved in the averaging technique. To this end we introduce a new function \(E_v^{(\text{meas})}\) in the \((H_1, H_2)\)-plane as follows:
\[
\begin{align*}
\bar{E}_v^{(\text{meas})}(H_1, H_2) & = E_v^{(1)}(H_1, H_2)  & H_1 < H_2, H_1 > -H_2 \\
\bar{E}_v^{(\text{meas})}(H_1, H_2) & = E_v^{(2)}(H_2, H_1)  & H_2 > H_1, H_1 > -H_2 \\
\bar{E}_v^{(\text{meas})}(H_1, H_2) & = E_v^{(3)}(-H_1, -H_2)  & H_1 > H_2, H_1 < -H_2 \\
\bar{E}_v^{(\text{meas})}(H_1, H_2) & = E_v^{(4)}(-H_2, -H_1)  & H_1 < H_2, H_1 < -H_2
\end{align*}
\]
(24)

where the superscripts 1 to 4 refer to the subsequent measurements considered in eqn. 22. Thus, the definition of \(E_v^{(\text{meas})}(H_1, H_2)\) includes the association of the measured values \(E_v^{(1)}(H_1, H_2), E_v^{(2)}(H_1, H_2), E_v^{(3)}(H_1, H_2)\) and \(E_v^{(4)}(H_1, H_2)\) to the points \((H_1, H_2), (H_2, H_1), (-H_1, -H_2)\) and \((-H_2, -H_1)\), respectively, where \(H_1 < H_2, H_1 > -H_2\).

Fig. 9 depicts the difference between \(E_v^{(\text{meas})}(H_1, H_2)\) and \(\bar{E}_v(H_1, H_2)\). The largest error committed by the averaging technique is observed for the minor-order branches between the field strengths \(-25 \rightarrow 45, 25 \rightarrow -45, 45 \rightarrow -25\) and \(-45 \rightarrow 25\).

Finally, the Preisach function, both for the CPM and the RPM, is obtained from the measured averaged
Everett function by

\[ P(\alpha, \beta) = -\frac{\partial^2 \hat{E}_a(H_1, H_2)}{\partial H_1 \partial H_2}, \quad \alpha = H_2, \beta = H_1 \]  

Fig. 10 shows the Preisach function while Fig. 11 illustrates the good agreement between the measured quasistatic \( B-H \) loop and the \( B-H \) loop, calculated by the Preisach model using the measured distribution function of eqn. 25.

Fig. 10  Resulting Preisach function corresponding with Everett function shown in Fig. 9  \( \Delta P = 150 \times 10^{-6} \)

Fig. 11  Measured and calculated quasistatic \( B-H \) loop, including minor-loop loop when enforcing piecewise linear magnetic field strength \( H \) with extreme values \(-300, 300, -60, 60, -300 \text{ A/m} \)

\[ \text{measured} \quad \quad \text{calculated} \]

5 Experimental verification

By numerous experiments we verified the magnetodynamic model, including either the CPM or the RPM, as outlined in Section 3. The numerical results which are obtained for relevant physical quantities, such as the \( B-H \) loops and the iron losses, are in good agreement with the values obtained by measurement.

The average magnetic induction \( B_a(t) \) through the lamination is enforced, according to

\[ \varphi = n B_{a,max} S \cos 2\pi f t \]  

where the frequency \( f \) varies from 0.1 to 400Hz and the induction \( B_{a,max} \) takes the values 0.8, 1 and 1.2T. Moreover, \( n \) stands for the number of laminations, while \( S \) is the surface of the cross section of one lamination. For these flux excitations the total electromagnetic losses per cycle and per unit volume, denoted by \( E \), are given by [8]

\[ E = E_h + E_e + E_e \]  

where the standard (quasistatic) hysteresis losses, the eddy-current losses and the excess losses (extra dynamic) are, respectively, given by

\[ E_h = 4 B_{a,max} H_{hyst} \]  

\[ E_e = \frac{4}{6} \sigma \pi^2 d^2 B_{a,max}^2 f \]  

\[ E_e = 8 B_{a,max} \sqrt{\sigma G S V_0 B_{a,max} f} \]

Here \( H_{hyst} \) and \( V_0 \) are fitting parameters with the dimension of the magnetic field, the latter describing the magnetic microstructure [8]. Recall that \( d \) and \( S \), respectively, stand for the half thickness and the surface of the cross section of the lamination as introduced in Section 3. Moreover, \( B_{a,max} \) and \( f \) are the amplitude of the average magnetic induction and the frequency, respectively, entering (eqn. 26). Finally, \( \sigma \) is the electric conductivity, appearing in eqn. 7, while \( G = 0.1357 \).

We emphasise that eqns. 27–30 only hold in cases where the skin effect may be neglected.

Fig. 12  Total iron losses and constituting parts as function of frequency \( (B_{a,max} = 1 \text{ T}) \)

\[ \begin{align*} \text{total} & \quad \varphi = E_h + E_e + E_e, \\ \text{RPM} & \quad \varphi = E_h, \\ \text{CPM} & \quad \varphi = E_h + E_e \end{align*} \]  

The measured value of the electrical conductivity \( \sigma = 30.7 \ 10^5 \text{S/m} \) has been

Fig. 12 gives the iron losses per cycle as a function of the frequency \( f \) when \( B_{a,max} = 1 \text{ T} \). This Figure reveals the very good coincidence of the measured electromagnetic losses (line with circles) and the numerically evaluated ones using the magnetodynamic model based on the RPM (full line), where the value of the electrical conductivity \( \sigma = 30.7 \ 10^5 \text{S/m} \) has been
measured directly. Here we were able to use a fixed value of \( k \), viz. \( k = 55 \text{m/As} \), for all frequencies considered. Apparently the iron losses evaluated with the CPM (dashed line) underestimate the measured total losses, but are in good agreement with the values obtained by summing up the standard hysteresis losses \( E_h \) and the eddy-current losses \( E_e \), given by eqns. 28 and 29 (dotted line). Thus, the use of the RPM technique allows one to properly account for the extra dynamic losses \( E_e \), given by eqn. 30.

In Fig. 13 the total iron losses are plotted as a function of the frequency for the induction levels \( B_{\text{max}} = 0.8, 1 \) and \( 1.2 \text{T} \). The numerical results are obtained by the magnetodynamic model eqns, 9, 12 and 13, describing the interaction between hysteresis and eddy-current effects, resulting in the space and time variation of \( B \) and \( H \).

Again we found a striking coincidence between the measured iron losses and those obtained numerically with the RPM technique when using the same value of the parameter \( k \), viz. \( k = 55 \text{m/As} \), for all frequencies and induction levels considered. The fact that this coincidence is observed, when using the same suitably taken value of the parameter \( k \), is in agreement with a remark in [8]. These authors state that eqn. 2, which involves the parameter \( k \), describes the basic property of domain wall dynamics in metallic systems. In this theory, \( k \) is not merely a fitting parameter but appears to be an extra material parameter related to the dynamics of the magnetic microstructure.

As a further illustration of the separate influence of the eddy-current action and the RPM technique on the dynamic loop shape, we give the \( B-H \) loops for the case that \( f = 400 \text{Hz} \) and \( B_{\text{max}} = 1.2 \text{T} \) in Fig. 14. The eddy-current action is reflected in the difference between the dashed–dotted loop and the loop in broken line, while the extra dynamic losses are related to the difference of the area enclosed by the loop in full line and the one in dashed–dotted line.

6 Concluding remarks

We have dealt with a mathematical method for the evaluation of the total iron losses in nonoriented steel laminations for arbitrary excitations. The Preisach hysteresis models, both the CPM and the RPM, are coupled with the magnetodynamic field calculations. The global model allows one to explain and predict the hysteresis behaviour of the magnetic materials considered. Here the relevant Preisach function, characterising the magnetic behaviour of the material, has been constructed out of an averaged measured Everett function, which has been defined in a suitable effective way so as to retain basic symmetry properties in the \((H_1, H_2)\)-plane.

The experimental verification revealed that the RPM is considerably more accurate than the CPM in describing the magnetodynamic behaviour of the material considered.

7 Acknowledgments

This research was carried out within the frame of the Interuniversity Attraction Poles for fundamental research funded by the Belgian state and with the financial help of the Ministry of Economy of the Flemisch Government in collaboration with OCAS, the research centre of Arbed-Sidmar ALZ. One of us (R.V.K.) thanks the Belgian National Foundation for Scientific Research (NFWO) for financial support.

8 References


