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On the No-Load Iron Losses Calculations of a SMPM Using VPM and Transient Finite Element Analysis

Hafedh Trabelsi, Ali Mansouri and Mohamed Hedi Gmiden

Renewable Energy and Electric Vehicles Unit, Engineering school of Sfax, Tunisia
ENIS, Route de Soukra, Km 3.5-BP W, 3038 Sfax
Fax : 216-74 275 595
E-mails: hafedh.trabelsi@enis.rnu.tn ; mansouriali2002@yahoo.fr ; gmiden2002@yahoo.fr

Abstract—*Iron losses modeling is an important task for analysis of rotating permanent magnet machines, because of their complicated structure and the rotational behavior of magnetic fields. The aim of this paper is the computation of no-load iron losses in a surface-mounted-permanent magnet motor (SMPM). The computational method consists of the Vector Preisach Model (VPM) incorporated into transient finite element analysis (FEA), which are coupled with analytical iron losses models. The iron losses have been computed with three methods: computing iron losses with purely alternating field; computing iron losses by summing the losses produced by the orthogonal components of the magnetic field; computing losses by using adequate models tacking into account the rotating behavior of the magnetic field. The developed method tacks account the hysteretic behavior in ferromagnetic materials. A special attention is paid to the investigation of the B-H relationship in ferromagnetic regions, to the analytical modeling of iron losses, and to the rotating behavior of the magnetic field. The calculation results are discussed.*

Keywords: *Hysteresis loop, Preisach Model, transient, finite element analysis, core losses, permanent magnet machine.*

1. Introduction

The accurate design of an efficient electrical machine requires the knowledge of iron losses in the magnetic circuit. Furthermore, some complex phenomena which are associated with iron losses make from this task a difficult problem.

Many studies are performed on the iron losses modeling in induction machines [1], [2], [3], whereas the studies concerning permanent magnet machines are fewer. In this paper, an investigation of iron losses prediction at no-load operation in a surface-mounted permanent magnet motor has been outlined.

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In a large number of commercial FEA packages, single-valued B-H relationships are usually adopted for ferromagnetic materials which neglects the hysteretic behavior in iron core regions, but the estimation of iron losses may be made a posteriori [4], [5], and [6].

An efficient way to estimate accurately iron losses is to incorporate the hysteresis phenomenon into FEA field equations. Doing so, the neglect of the irreversible materials behavior has been overcome. The subject of this paper is not to implement the technique of hysteresis in FEA, which has been outlined in other work [7], but to investigate the impact of the hysteresis model on the iron losses the estimation.

The hysteresis model used in this work is the vector Preisach model incorporated in FEA in a reversed fashion. Unlike the hysteresis, the inclusion of the eddy current effects in the magnetic field is not outlined in this paper, but eddy current losses are estimated by using adequate empirical formula.

In this work the transient FEA has been used for the computation of no load iron losses in a SMPM by three methods. A special attention is given to the calculation method and the B-H relationship in ferromagnetic regions.

In PM motors, stator iron losses can form a large proportion of the total losses. This is partly caused by the really low rotor loss due to the low time variation of the flux density.

2. Analysis methods

In this work the FEA investigation has been made up under transient conditions. The iron rotor core has been modeled by a single valued B-H function; this is due to the fact that the hysteresis loss in the rotor running at synchronous speed is not significant.

The hysteresis in the stator core has been modeled by two methods:

- Considering a single-valued function,
- Incorporating the hysteresis into FEA computation,

Since the first method has been adopted by previous works, we are going to concentrate on the second one in which the hysteresis in the stator core is handled by means of the vector Preisach model, consisting of angularly distributed scalar models, and applied in a reversed manner.

The interface between the FEA and VPM is obtained by means of the fixed-point technique iterative procedure. In which the relationship between B and H is written as follows [8]:

$$B = \mu H + R \tag{1}$$

Where μ is the fixed-point coefficient and R is a residual founded iteratively.

Coupling equation (1) to appropriate Maxwell equations, the magnetic problem is formulated in terms of magnetic potential vector. The problem solution starts with an arbitrary given value of R, providing the magnetic potential vector A, from which B is calculated to supply an input for VPM giving the value of H. With B and H already known, a new value of R is calculated using formula (1). This value is again supplied in FEA equations. This procedure is repeated until the problem convergence is reached.

3. Iron losses calculation

The conventional model separates the iron losses into three terms [4] being the static hysteresis losses P_h, the classical eddy current loss P_c and excess loss P_e.

3.1 Iron loss with purely alternating field

For a sinusoidal magnetic flux density B, the iron loss power density is given by [1] [9]:

$$P = P_h + P_c + P_e$$

$$P_h = k_h f B_m{}^{\beta} \tag{2}$$

$$P_c = \frac{\sigma d^2}{12} \frac{1}{T} \int_T \left(\frac{dB}{dt} \right)^2 dt \tag{3}$$

$$P_e = k_e \frac{1}{T} \int_T \left| \frac{dB}{dt} \right|^{1.5} dt \tag{4}$$

Where:

f frequency of the magnetic flux waveform,
B_m peak of the sinusoidal flux density,
B flux density
B Steinmetz constant
k_h hysteresis constant
σ material conductivity
d lamination sheet thickness
K_e excess loss constant

Core losses can be obtained by discretizing (2), (3) and (4) in the time domain where stepped FEA is used.

By performing transient FEA, the peak value of flux density during a period in each element can be found. The hysteresis loss in the stator is expressed as follows:

$$P_h = 2 p k_h L f \sum_{i=1}^{Ne} A_i B_{m,i}{}^{\beta} \tag{5}$$

Where p, L, A_i, N_e, $B_{m,i}$ are respectively the pair pole number, the stack length of the stator, the area of the finite e element i, the total number of finite elements mesh, and the peak value of flux density in element i.

Applying the same procedure to equations (3) and (4), the classical eddy currents loss and excess loss can be expressed as follows:

$$P_c = 2p\frac{\sigma d^2}{12} fL\sum_{i=1}^{N_e} A_i \int_T \left(\frac{dB_i}{dt}\right)^2 dt \tag{6}$$

$$P_e = 2pk_e fL\sum_{i=1}^{N_e} A_i \int_T \left|\frac{dB_i}{dt}\right|^{1.5} dt \tag{7}$$

Where B_i is the flux density in element number i.

Equations (5)-(7) are used for the computation of the total iron losses in two cases: (i) modelling ferromagnetic materials by single valued B-H relationship (ii) considering the hysteresis effect by VPM. The obtained results are illustrated in table 1. A fourth of the machine subject of investigation is illustrated in figure 1.

	Single valued BH curve	VPM
Eddy current losses (w)	11.57	12.7
Hysteresis losses (w)	33.49	30.84
Excess losses (w)	4.51	4.32
Total losses (w)	49.57	47,86

Table 1: iron losses produced by alternating field

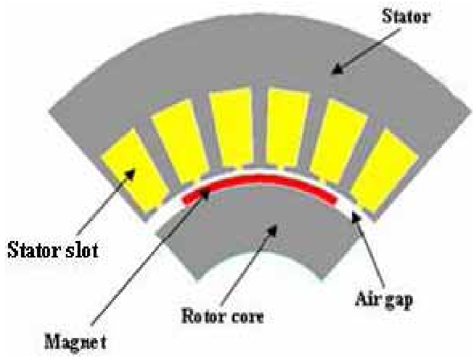

Figure 1: Fourth of the studied topology [10]

3.2 Iron loss with orthogonal components

In a permanent magnet motor, the variation of the flux density in ferromagnetic core is far from alternating. In this situation, the rotating behaviour of the flux density should be considered. An other approximation to predict the core losses in an electrical machine is to consider both spatial components of the flux density. In this case, the losses produced by orthogonal components are considered to be independent. Doing so, the rotational iron losses have been predicted by summing up the losses produced by the two components [11], [12], [13] and [14].

Applying (5)-(7) to the orthogonal components of the magnetic flux density obtained by FEA, the core losses have been estimated with and without hysteresis effect.

	Single valued BH curve	VPM
Eddy current losses (w)	31.10	32.51
Hysteresis losses (w)	31.48	30.45
Excess losses (w)	9.5	11.705
Total losses (w)	72.08	74.665

Table 2: iron losses produced by orthogonal field components

3.3 Iron loss by using adequate models

The assumption of alternating field in iron core of a rotating machine is very questionable because the induction in both stator teeth and core is significantly rotational. This will be illustrated in the following sections. This affects the iron loss value because rotational flux causes an increase of the classical eddy current losses as far as hysteresis losses [2]. The second method, in which the losses are calculated by summing up losses provided by orthogonal components, assumes the independence between the losses produced by orthogonal components; this is not true in all cases. So, the rotating behaviour of the magnetic flux should be considered when predicting iron losses for a permanent magnet machine. In [9], an analytical model tacking into account the rotating losses has been developed, and it will be adapted in the rest of this paper. The considered model is as follows:

$$P_c = 8.p.k_c.N.f^2.L.\sum_{i=1}^{Ne} A_{ei}\left(\begin{array}{l}\sum_{j=1}^{N}\left(B_{ex,tj}-B_{ex,tj-1}\right)^2+\\ \sum_{j=1}^{N}\left(B_{ey,tj}-B_{ey,tj-1}\right)^2\end{array}\right) \tag{14}$$

where A_{ei}, N_e, p and L are respectively the area of the finite element e_i, the total number of finite elements, the pair pole number and the stack length of the stator.

Applying the same procedure to equation (8) the excess losses can be written as.

$$P_e = 2.\mathrm{p}.\frac{\mathrm{k_e}}{\mathrm{C_e}}.\mathrm{f}^{1.5}.(2.\mathrm{N})^{0.5}.\mathrm{L}.\sum_{i=1}^{Ne} A_{ei}.\left(\sum_{j=1}^{N}\left(\begin{array}{l}\left(B_{ex,tj}-B_{ex,tj-1}\right)^2+\\ \left(B_{ey,tj}-B_{ey,tj-1}\right)^2\end{array}\right)^{0.75}\right) \tag{15}$$

$$p_h(t) = 2.p.f.L.\sum_{I=1}^{Ne} A_{ei}.\int_{\frac{T}{2}} \left(\left| H_{ex,ti} \frac{dB_{ex,ti}}{dt} \right|^{\frac{2}{\beta}} + \left| H_{ey,ti} \frac{dB_{ey,ti}}{dt} \right|^{\frac{2}{\beta}} \right)^{\frac{\beta}{2}} \tag{16}$$

Applying equations (14)-(16) to the studied motor, iron losses have been investigated. The obtained results are summarized in table 3

	Single valued BH curve	VPM
Eddy current losses (w)	31.10	32.51
Hysteresis losses (w)	40.15	25.35
Excess losses (w)	5.87	6.2
Total losses (w)	77.12	64.06

Table 3: Iron loss adequate models

4. Flux vector in SMPM

In order to show the rotational behavior of the vector flux density and the B-H relationship in the studied machine, the variations of the magnetic flux density and intensity (radial and tangential components) in the studied machine have been computed during the transient FEA in the middle, the roots of the stator teeth, and in the middle of stator yoke.

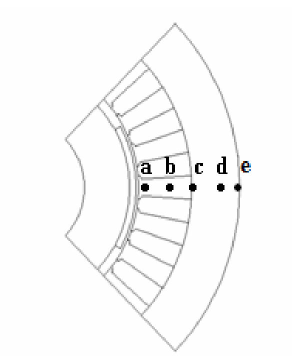

Figure 2: Points for witch the flux density have been computed

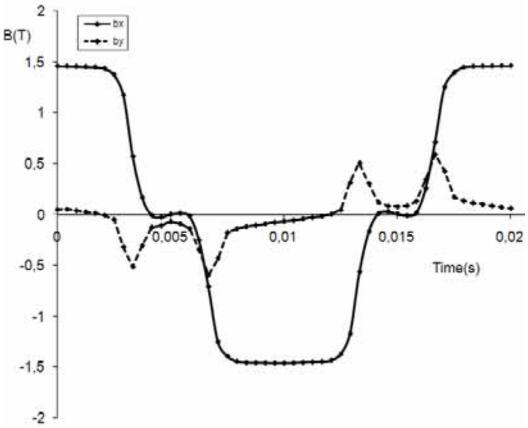

Figure 3: B-loci: point A

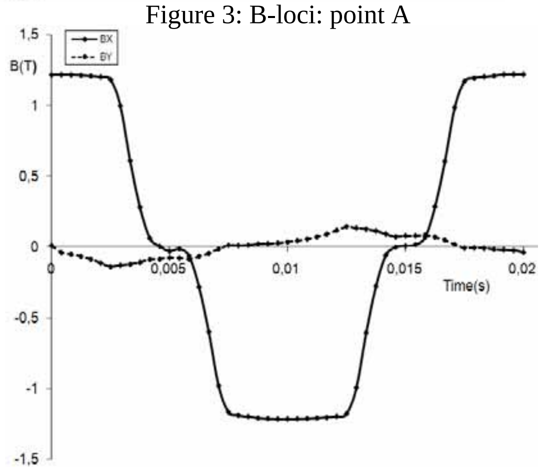

Figure 4: B-loci: point B

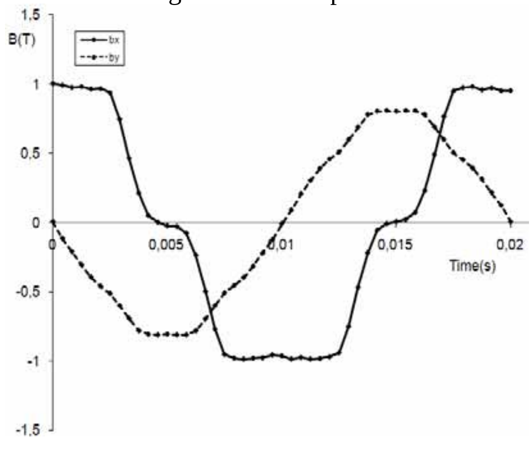

Figure 5: B-loci: point C

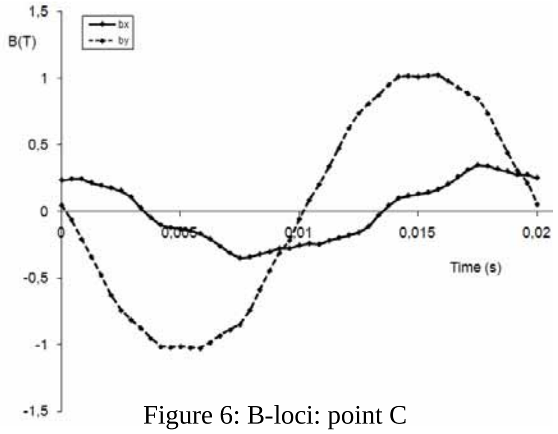

Figure 6: B-loci: point C

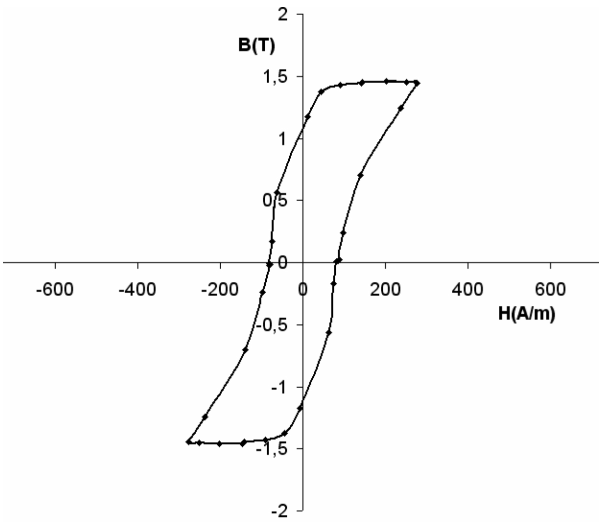

Figure 7: Bx-Hx: point A

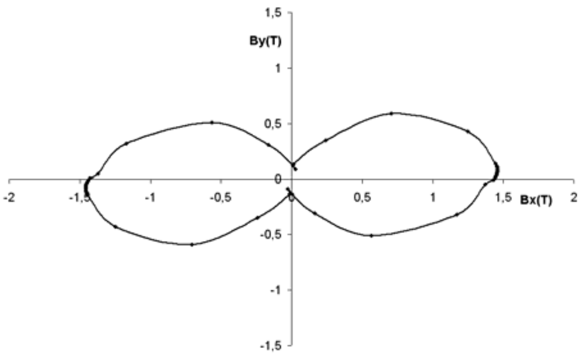

Figure 8: By-Bx: point A

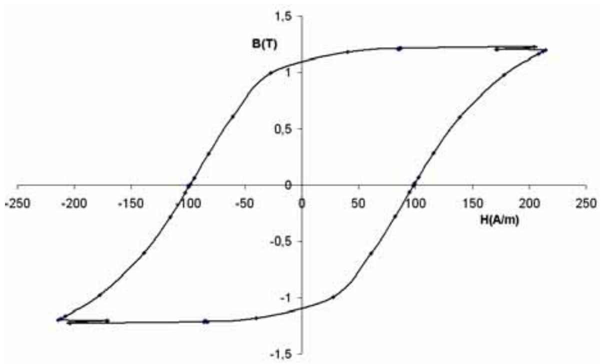

Figure 9: Bx-Hx: point B

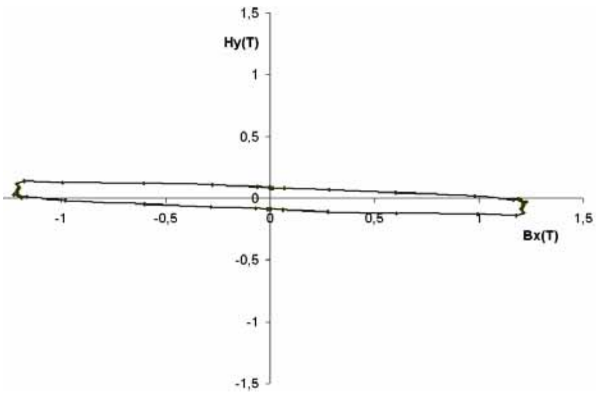

Figure 10: By-Bx: point B

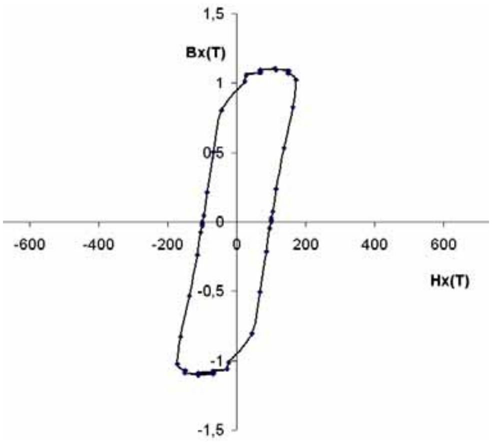

Figure 11: Bx-Hx: point C

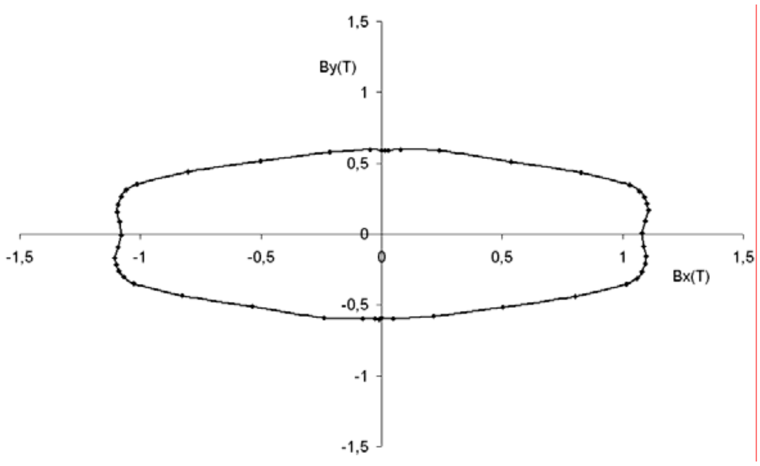

Figure 12: By-Bx point C

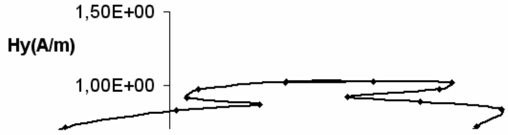

Figure 13:Hy-By: point D

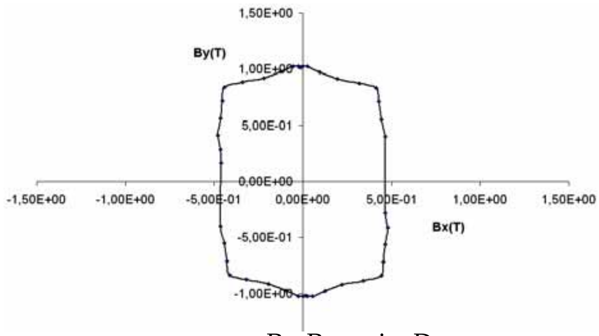

Figure 14: Bx-Bx: point D

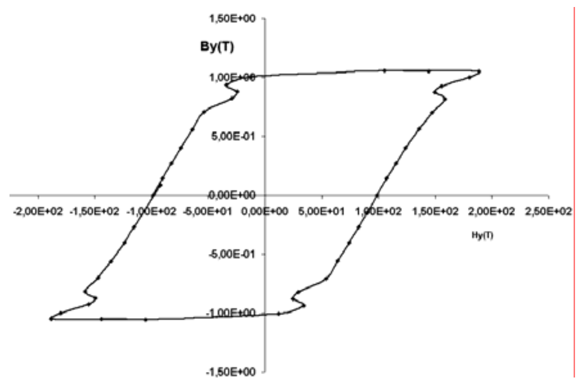

Figure 15: Hy-By: point E

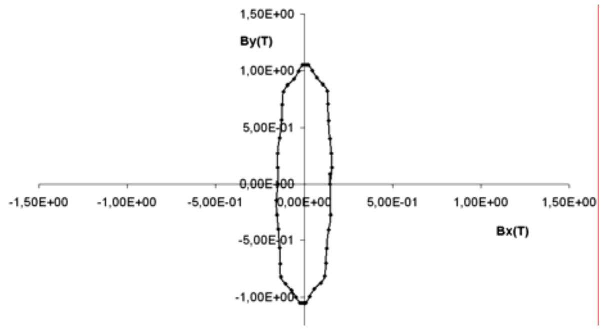

Figure 14: By-Bx: point E

5. Results discussion

Method	Single valued BH curve	VPM
1	49.57	47.86
2	72.08	74.665
3	77.12	64.06

Table 4: Iron loss calculation

Table 4 shows the summary of the results obtained in the previous sections

- Considering the losses as purely alternating (method 1)
- Calculating iron losses by adding the losses produced by the two spatial components (method 2),
- Applying an adequate model (method 3),

The iron loss difference between methods 1 and 2 is mainly due to the non sinusoidal flux density waveform in critical regions of PM motors. The fact that the flux density variation is not sinusoidal greatly influences the eddy current losses, as the induced circulating current is a function of dB/dt.

The impact of the non sinusoidal flux density on eddy current losses is clearly noticed: an increase of the eddy current losses was noticed. In spite of the gain brought by this second method, this method is not more accurate, this is due to the assumption of independent losses produced by orthogonal components, which is not true in reality.

The results obtained by the third method are considered more accurate than the other two; the accuracy of the last method has been validated in [9]. On one hand, method 1 underestimates the total losses because it neglects the losses produced by one of the spatial components of the flux density. On the other hand, method 2 over predicts the total losses (in the case of modelling the hysteresis phenomenon); this is due to the fact that the losses produced by orthogonal components are dependent. The major advantage of the second method is that it is possible to bound the error in iron loss calculation. The model proposed in method 3 overcomes the estimation errors generated by the two others, especially on the hysteresis term losses. This model is able to consider the effects of the time rate of change of the vector flux density and predicts hysteresis losses with good accuracy.

The difference between the results obtained with a single valued BH curve and those obtained with Preisach model are due to the method of which H is calculated. In the first one H is calculated directly from a non linear BH curve, whereas in the second one H is computed from the inverse Preisach model. The incorporation of the VPM directly in FEA allows arbitrary variation of the flux density, which results into hysteresis branching to be taken into account. Figures 3-6 show the B-loci in four points in the stator, the position of which is indicated in figure 2. It is clear that the induction is significantly rotational, inconsistent with the assumption of alternating field. Rotational fields cause an increase of the classical eddy current losses, which has been clearly noticed in methods 1 and 2.

Figures 7, 9, 11, 13 and 15 illustrate the BH relationship for the five considered points; we can notice clearly the hysteretic relationship between B and H and the ascendant and descendant branches of the obtained cycles are not monotonous. The reason is that when the magnetic flux density varies more slowly, there are fewer eddy currents in the material and the necessary field to obtain a given B is less important than for higher values of dB/dt.

6. Conclusion

The no-load iron losses of a surface mounted permanent magnet motor have been predicted by using three methods and for two cases: using a single valued BH curve and inverse vector Preisach model for the ferromagnetic materials.

Computation of iron losses by assuming a purely alternating field may be acceptable in some applications in which the rotating losses could be neglected. As a consequence, the iron losses are under predicted.

Calculating iron losses by summing up the losses produced by orthogonal components can bound the error in the loss estimation by the purely alternating field method, but it is not more accurate especially in no load operation conditions. Whenever possible, a corrected model should be developed to improve the accuracy in iron losses estimations under rotating field's behavior.

An investigation of the BH relationship in five points in the stator has been made up. It has been confirmed on one hand the non alternating behavior of the magnetic field, and on the other hand the hysteretic behavior of this relationship.

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