Effect of Iron Loss on the Performance of Interior Permanent Magnet Machines

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ABSTRACT

In recent years, the Interior Permanent Magnet (IPM) machine has been adopted for many high performance applications that require high efficiency over a wide speed range. Due to its complex structure, flux density wave form of the IPM machine is not pure sinusoidal. Presence of higher frequency harmonics in the flux density can cause large iron loss, leading to degraded performance of the machine at high speed. In this respect, analysis and precise prediction of iron loss of such machines become an important issue. In this paper, different methods of predicting iron losses of the IPM machine such as empirical formula method, finite element prediction methods with and without rotational field loss, equivalent circuit modelling method have been discussed and applied to a laboratory IPM machine for experimental verifications. The relationship between armature reaction and iron loss at full load condition has been analysed. Affect on the iron loss of maximum torque per ampere and flux-weakening control strategies of the IPM machine is also investigated for the test machine.

1. INTRODUCTION

The Interior Permanent Magnet (IPM) machines is increasingly gaining attention from the research community due to its high torque per size ratio, absence of rotor copper loss and ability to run at extended speed with near constant power. In high performance applications, efficient utilization of the machine is a necessity. In IPM machines, a significant portion of the total loss comes from the iron loss, which becomes the ultimate limiting factor of its output capability at high speed. Therefore, it is essential to predict iron loss precisely at design stage for such machines. In this paper, different methods available in recent literature are reviewed and applied to a laboratory IPM machine. The predicted results of these methods are compared with measured values for accuracy level. The affect of maximum torque per ampere control and flux weakening strategy over the iron loss are also analysed for both no load and full load conditions.

2. IRON LOSS IN IPM MACHINES

Iron loss of magnetic material is conventionally measured with sinusoidal flux density of varying frequencies. The total iron loss is comprised of hysteresis and eddy current losses. The loss density [W/m^3] in a core material is expressed as,

$$p_{iron} = p_{hys} + p_{eddy} = k_{hys}\hat{B}^{\beta} f + k_{eddy}\hat{B}^2 f^2 \qquad (1)$$

where, f: frequency [Hz]

$\hat{B}$: peak of the sinusoidal flux density [T]

β: Steinmetz constant

k_{hys}: hysteresis constant

k_{eddy}: eddy current constant

However, the flux density in the core laminations in most of the electric machines including IPM machine is not pure sinusoid. In such cases, iron loss calculated from (1) using the peak value of the fundamental component of flux density would result in large discrepancy between estimated and measured values. Therefore, it is necessary to consider the losses due to the harmonics for an accurate estimation. The harmonic terms present in the flux density, primarily affect the eddy current loss. The affect of harmonics on eddy current loss can be accounted for simply by taking the square of rate of change of flux density for the duration of one time period [1].

$$p_{eddy} = \frac{2k_{eddy}}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt$$

(2)

Alternately, the flux density wave-form can be expanded as Fourier series of harmonic frequencies and the total iron loss can be calculated as the summation of loss contributed by each harmonics [2, 3].

Apart from hysteresis and eddy current loss, there exists an additional loss component known as, excess or anomalous loss, which is associated with continuous arrangement of magnetic domain configuration [4]. It is expressed as,

$$p_{exe} = \frac{k_{exc}}{T}\int_0^T \left(\frac{dB}{dt}\right)^{1.5} dt \qquad (3)$$

where, k_{exe} is excess loss constant

Hence, the total iron loss in the electric machine is summation of hysteresis loss, eddy current loss and excess loss.

The variation of flux density in the laminating material of electric machine is not only alternating but also rotating in nature. In conventional iron loss calculations loss caused by rotating field is often ignored. However, recent study is showing that iron loss due to rotating flux density in electric machine is not negligible. In order to achieve better accuracy of predicted loss in a practical machine loss due to rotating flux density variation needs to be included. Although there are quite a few methods available to predict iron loss, not all of them can incorporate additional loss due to rotating flux density variation.

2.1. METHODS

There are a number of methods available in recent literatures which predict iron loss of an IPM machine[2, 3, 5-8]. Depending on there modelling principles, these methods can be categorized as (i) Empirical formula method (ii) Finite Element (FE) method (iii) Equivalent circuit method.

2.1.1. EMPIRICAL FORMULA METHOD

In Empirical formula method, a set of approximate models are used to predict iron loss in PM machines. In [7], an improved empirical formula has been derived from the assumption of linear trapezoidal variation of flux density at stator teeth and yoke . The average eddy current loss density in stator tooth can be expressed as,

$$p_{e\_teeth} = 16 k_{eddy} k_c mq (B_{th} f)^2 \tag{4}$$

where, k_c : the correction factor for motor geometry,

m : number of phases,

q : number of slots per phase per pole,

B_{th} : the peak of flux density at teeth.

It has also been noticed in [7] that flux density changes at various layers of stator yoke. Based on these variations, a simplified model of yoke eddy current loss density has been developed,

$$p_{e\_yoke} = \frac{32}{\alpha} k_{eddy} k_r (fB_c)^2 \tag{5}$$

In (5), B_c is the peak value of the longitudinal component of the flux density in the stator yoke and k_r is a correction factor for the eddy current loss caused by the normal component of the flux density in yoke and is related to motor geometry by (6),

$$k_r = 1 + \frac{8 k_q d_y^2}{27 \alpha q \lambda^2} \tag{6}$$

where, k_q : correction factor for motor geometry,

d_y : yoke thickness,

λ : the projected slot pitch at the middle of yoke

α : magnet span.

The hysteresis loss densities at the tooth and yoke are simply expressed as function of frequency, and peak flux density at each part.

$$p_{hys\_teeth} = k_{hys} f B_{th}^{\beta}$$
$$p_{hys\_yoke} = k_{hys} f B_{yk}^{\beta} \tag{7}$$

The total iron loss is given as,

$$p_{iron} = (p_{e\_teeth} + p_{hys\_teeth}) V_{teeth} + (p_{e\_yoke} + p_{hys\_yoke}) V_{yoke} \tag{8}$$

where, V_{teeth} and V_{yoke} are the volume of the teeth and yoke of the machine.

In design stage, empirical formula method is very useful to get a quick idea of iron loss in the machine. However, accuracy of the results heavily depends on precise knowledge of machine dimensions and correction factors. The empirical formula method is applied to a laboratory IPM machine. The geometry of the machine is shown in Figure 1. Dimensions of the machine are given in Table 1. The loss calculated by this method is compared with the measured iron loss of the test machine in Figure 2. The accuracy of the method is discussed in section 2.2 along with other methods.

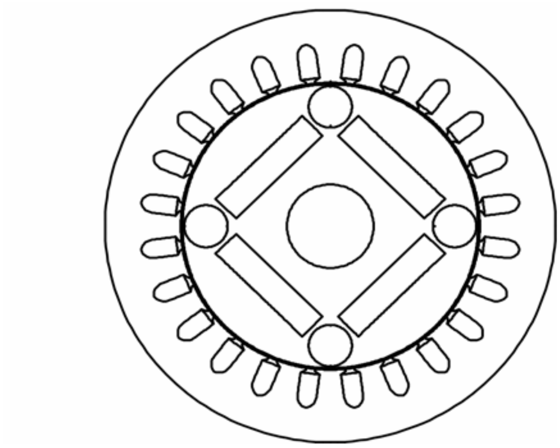

Figure 1: The geometry of the laboratory IPM machine

Table1: Dimension of the IPM machine

Name	Quantity
Number of Poles	4
Stator and rotor core material	Non linear steel
Bridge thickness	2 [mm]
Stator outer Diameter	126[mm]
Core length	55[mm]
Rotor Outer Radius	40.5[mm]
Stator Inner Radius	41[mm]
Air gap length	0.5[mm]
Number of series turns per phase	23
Number of slots	24
Thickness of the Magnets	8[mm]
Slot opening	2.56[mm]
Tooth width	5.3[mm]
Tooth hight	11.45[mm]
Yoke depth	11.5[mm]
Tooth Volume	8.3848e-5[m^3]
Yoke volume	2.594e-4 [m^3]

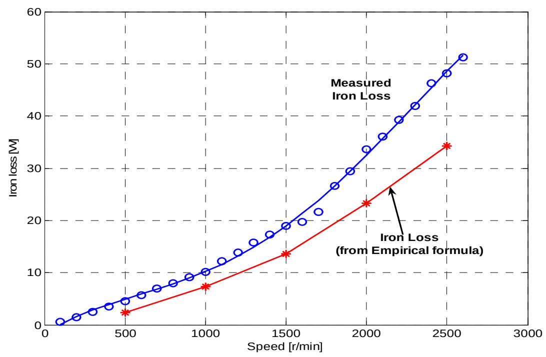

Figure 2: The iron loss calculated form the empirical formula method

2.1.2. Finite Element Method (FEM)

There are two different approaches to calculate iron loss of an electric machine in finite element models. In the first method, the flux density vector of each element is spread out as a Fourier series of j^{th} elliptical harmonics. The major axis and minor axis flux density and their ratio δ_e are determined and total iron loss is calculated as the summation of hysteresis loss, eddy current loss and excess loss [2]. The loss densities are expressed as,

$$p_{hys} = \sum_{j=0}^{\infty}[\delta_{ej} p_{r\_hys_j} + (1-\delta_{ej})^2 p_{a\_hys_j}] \quad (9)$$

$$p_{eddy} = k_{eddy}\sum_{j=0}^{\infty}\left[(jf)^2(B^2_{(maj)_j} + B^2_{(min)_j})\right] \quad (10)$$

$$p_{exe} = k_{exe}\frac{1}{T}\int_0^T\left[\left(\frac{dB_x}{dt}\right)^2 + \left(\frac{dB_y}{dt}\right)^2\right]^{3/4} \quad (11)$$

where, p_{r_hys} and p_{a_hys} are rotational and alternating hysteresis losses calculated with flux density of B_{maj} at fundamental frequency of f, B_x and B_y are the x and y components of flux density vector.

In this method, the loss due to rotational magnetic field is also included; hence, it can give a fairly good estimation of the iron loss in the IPM machine. However, it is cumbersome and need a large number of iteration for different operating condition.

The second approach to calculate iron loss in finite element model is to use time stepped FE analysis with a rotating air gap. The iron loss over one complete period of a magnetic region is expressed as,

$$P_{iron} = pk_f\sum_{i=1}^{l}A_iL\left[k_{hys}B_m^{\beta}f + \frac{2k_{eddy}}{T}\int_0^T\left(\frac{dB}{dt}\right)^2 dt + \frac{k_{exe}}{T}\int_0^T\left(\frac{dB}{dt}\right)^{3/2} dt\right] \quad (12)$$

where, p is the number of pole pairs in the machine, A_i is the area of i^{th} element, L is the total depth of the machine, k_f is the stacking factor and B_m is the peak flux density in the i^{th} element. This method is capable to take in to account of losses due to alternating field and its harmonics but not of rotating field. Since loss due to rotational flux density is significant in IPM machine, loss calculated from (12) will be less than measured loss.

As mentioned earlier, in electrical machines the additional iron loss occurs due to rotational variation of magnetic flux density. In stator core, rotational variation can be observed at the roots and forefront of the teeth and back side of the slots. The additional loss caused by this rotational field depends on the ellipticity of the flux density wave form.

In [3] a simplified expression has been derived for rotational loss. The flux density wave-form over one time period is estimated at various points of stator tooth and yoke. The ellipticity of these waveforms are determined and iron loss density due to rotational filed is calculated as,

$$p_{rot\_iron} = \gamma\delta_e p_{a\_iron}$$
$$p_{rot\_iron} = \gamma\sum_{j=1}^{n}\sum_{i=1}^{l}\delta_{e(ji)}g_i\{k_{hys}jfB^{\beta}_{m(ji)} + k_{eddy}(jf)^2B^2_{m(ji)}\} \quad (13)$$

where, p_{a_iron} is the iron loss due to alternating field variation, $B_{m(ji)}$ is $L_{maj(ji)}/2$, $L_{maj(ji)}$ is the length of major axis of the j^{th} harmonic flux density vector of the i^{th} element, l is total number of elements, n is total number of harmonics, g_i is the mass of i^{th} element, and γ is the rate of iron loss increment under rotational field to alternating field. The total loss due to rotational and alternating flux density can be expressed as,

$$p_{iron} = (1+\gamma)\sum_{j=1}^{n}\sum_{i=1}^{l}\delta_{e(ji)}g_i\{k_{hys}jfB^{\beta}_{m(ji)} + k_{eddy}(jf)^2B^2_{m(ji)}\} \quad (14)$$

The predicted iron loss by this method is very close to the measured values.

In order to calculate iron loss by the FE method, a model of the laboratory machine has been constructed. The iron loss due to alternating flux density is calculated from a time steped finite element analysis and rotational losses are calculated from (13). The iron losses calculated by FEM with and without rotational loss are compared to the measured loss in Figure 3 and discussed in section 2.2.

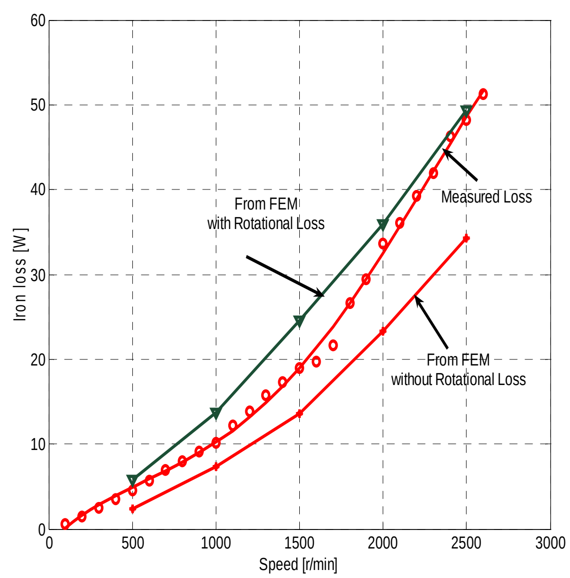

Figure 3: Iron loss calculated from FEM method

2.1.3. Equivalent circuit method

The no load input power of the IPM machine is consists of no load copper loss, mechanical loss and iron loss. The iron loss along with the mechanical loss is obtained by subtracting the copper loss from the input power. However, mechanical loss can be separated only by using a pseudo rotor. The pseudo rotor should have same core material and mass of the real rotor but without the magnetic fields. Consequently, the test requires extra arrangement. In [8] a simpler method has been described which requires no special arrangement and seems to give some idea of iron loss in a test machine. In this method, the two axes equivalent circuit of the IPM machine that includes an iron loss resistance is taken as the basis of analysis. The equivalent circuit is shown in Figure 4.

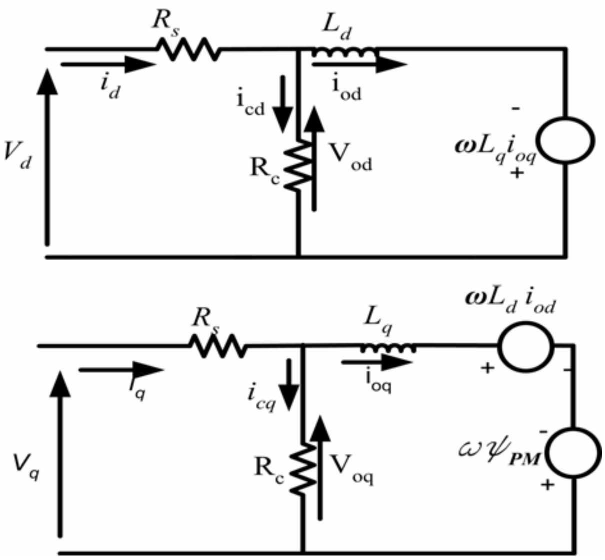

Figure 4: Equivalent circuit of the IPM machine including iron loss resistance

The steady state d- and q- axes equations of the IPM machine are,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + \dfrac{\omega^2 L_d L_q}{R_c} & -\omega L_q \\ \omega L_d & R_s + \dfrac{\omega^2 L_d L_q}{R_c} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \dfrac{\omega^2 L_q \Psi_{PM}}{R_c} \\ \omega \Psi_{PM} \end{bmatrix} \quad (15)$$

where ω is the electrical speed, v_d , v_q, i_d, i_q and L_d, L_q are d-and q-axes voltages, currents and inductances respectively, Ψ_{PM} is the magnet flux linkage, R_s and R_c are the equivalent copper- and iron-loss resistances.

The iron loss can be estimated as,

$$p_{iron} = \frac{\sqrt{v_d^2 + v_q^2}}{R_c} = \frac{\omega^2}{R_c}\left\{\left(\Psi_{PM} + L_d i_{od}\right)^2 + \left(L_q i_{oq}\right)^2\right\} \quad (16)$$

Neglecting iron loss due to harmonics and assuming Steinmetz constant β as 2, (1) can be expressed as function of total air gap flux density. It leads to the common equivalent resistance R_c for both axes as shown in Figure 4.

Running the test IPM machine at no load with $i_d = 0$, the value of R_c can be calculated as,

$$R_c = \frac{v^2 - \omega^2(\Psi_{PM} + (L_d - L_q)i_q^2}{P_{in} - \omega \Psi_{PM} i_q - i_q^2 R_s} \quad (17)$$

where, $P_{in} = v_q i_q$, $v^2 = v_d^2 + v_q^2$

However, in this method discrepancy between measured value and estimated ones increases with speed because it is modeled on the basis of (1), which does not include harmonic and rotational losses. The accuracy of the values also depends on precise estimation of frequency and magnet flux linkage. The estimated iron loss of the laboratory IPM machine by the above mentioned method is compared with measured values in Figure 5.

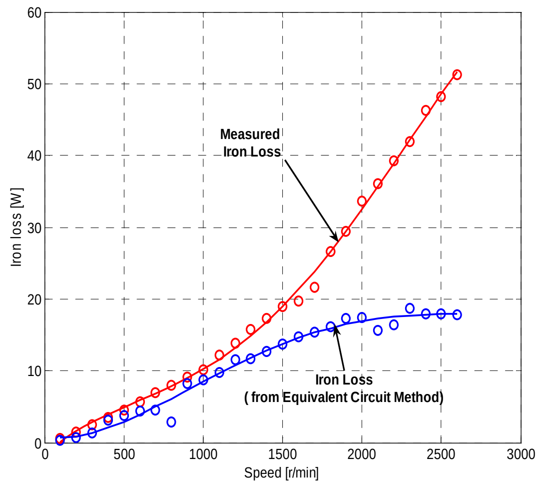

Figure 5: Iron loss calculated from equivalent circuit method

2.2. Comparison and discussion

The iron losses estimated from all three methods discussed above, along with the measured losses are shown in Figure 6. It is obvious from the figure that, losses estimated by all methods are very close to measured loss at low speed. However, difference increases with growing speed except in case of FEM prediction with rotational field loss. It can be concluded from these observations that iron loss due to rotational flux density becomes more and more significant with speed. The equivalent circuit model suffers most because in this model losses due to harmonics in flux density as well as losses due to rotational field are neglected. Either FEM method without rotational loss or empirical formula method can be used to estimate loss of any IPM machine during design process when speed range is low. However, for high speed IPM machines, losses due to rotational field can not be neglected. Loss due to higher order harmonics and rotational field both becomes significant with increasing speed and neglecting these losses will result in compromised accuracy.

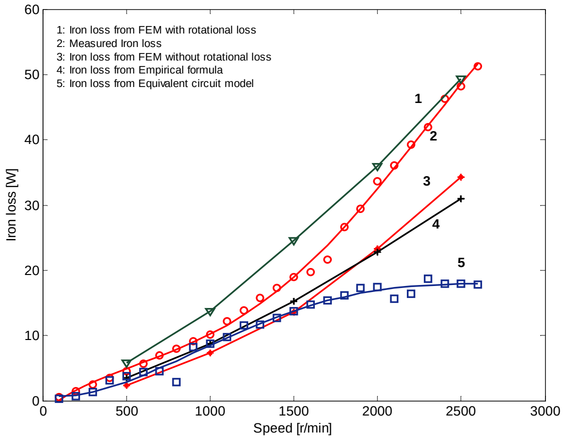

Figure 6: Comparison of iron losses of the test machine obtained from different methods

3. Iron Loss at Full Load

The iron losses estimated above by different methods are done at no load. In such condition, stator current is very small; hence affect of armature reaction is insignificant. However, at full load, in the IPM machine, effect of armature reaction can no longer be ignored. Due to smaller air-gap, armature reaction can alter air-gap flux significantly [9]. Normally, the IPM machine is run with maximum torque per ampere (MTPA) control strategy at zero to base speed range and with flux weakening control strategy at higher than base speed. In MTPA control, the current angle is maintained in such a way that maximum torque is achieved. On the other hand, in the flux weakening control the negative d- axis current is increased to offset the growing back EMF of the machine so that constant rated terminal voltage can be maintained at higher speeds. The air-gap flux density at no load and at full load with MTPA for 1500 r/min is shown in Figure 7(a). At full load air-gap flux has been altered considerably which means harmonics in the MMF wave form have increased leading to a higher iron loss at full load. In flux-weakening strategy, air-gap flux density has been reduced by the negative d-axis current but harmonic content in the resultant MMF waveform remains high. It is shown in Figure 7(b). As a result, iron loss in flux weakening may not reduce, rather increase with speed. In Table 2 iron loss at no load and full load in MTPA and flux-weakening operating conditions of the same machine are shown.

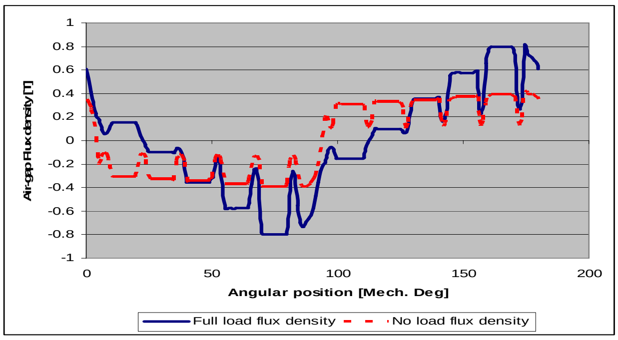

Figure 7(a): Air-gap flux density at no load and full load with MTPA

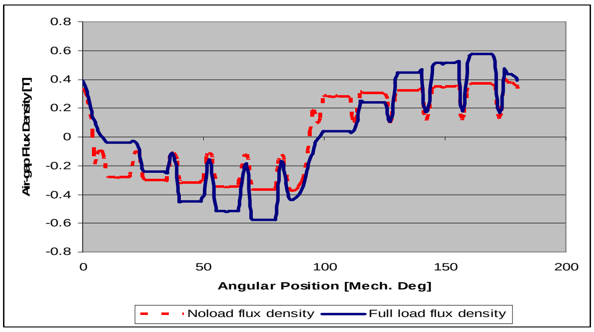

Figure 7(b): Air-gap flux density at no load and full load with Flux-weakening

Table 2: Comparison of no load and full load losses

Operating Conditions	MTPA (1500 r/min)	Flux-Weakening (2100r/min)
Full Load	30.77 W	70.90 W
No Load	18.98 W	32.52 W

4. Conclusion

In this paper, different methods of iron loss calculation for the IPM machine have been discussed. It has been seen that all the methods predict iron loss very close to measured value at low speed. However, in all methods except in the FEM with rotational field loss, predicted values becomes lower than the measured ones at high speed. The empirical formula method and FEM method without rotational field losses gives comparable result. In both methods, rotational field loss has been ignored. As a result they deviate from the measured values at high speed. In case of the equivalent circuit models, discrepancy between measured valued and estimated value grows higher with speed because of neglected harmonic losses as well as rotational field losses. The FEM that includes rotational field loss predicts loss very close to measured value even in high speeds. It can be concluded that for high speed IPM machines accuracy of iron loss prediction becomes high when harmonic loss and rotational field loss both are included. The iron loss of full load condition of the IPM machine is also investigated for both MTPA and flux weakening control. It has been seen that full load iron loss is higher than no load iron loss for a particular speed due to higher harmonics in the MMF wave form caused by larger armature reaction.

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