Calculation Of Iron Losses In Induction Machine Using FEM Considering Time Harmonics

Kindl Vladimir, University of West Bohemia in Pilsen (9.28.2009, Doc. Ing. Bohumil Skala, Ph.D, Department of Electromechanics and Power Electronic)

Abstract

Pulsation losses, which are very difficult to measure, are present in every squirrel cage induction motor and depend mainly on the geometrical design of iron core. A two-step method for computing the iron losses in a squirrel cage induction machine is proposed. As a first step the flux density in the cross section of the motor is evaluated using a FEM model neglecting hysteresis and eddy currents in the laminated core. The second step is practically the usage of equations (empirically found) computing both iron and eddy current losses

1. INTRODUCTION

Iron core losses are usually divided into two components: The hysteresis losses and the eddy current losses. Hysteresis losses:

The area of the hysteresis loop (significant for magnetic materials) represents the energy loss during one cycle in a unit cube of the core material. The hysteresis loss per supply cycle is given by closed integral of hysteresis loop multiplied by such volume. It is clear, that this calculation cannot be done using FEM. Fortunately; there is another way of evaluation this loss (described below).

Eddy current losses:

As well known, the core of an electrical machine's armature is made from soft iron, which is a conducting material with desirable magnetic characteristics. This material will have currents induced at it when varying magnetic flux acts on. These currents are so called EDDY CURRENTS. The power dissipated in the form of heat, as a result of the eddy currents, is considered as a loss. Eddy currents, just like any other electrical currents, are affected by the resistance of the material in which the currents flow. We unfortunately cannot evaluate these losses by means of iron material models settings (assign of electrical resistivity into iron core). This is because of the fact, that 2D, neither 3D model is not able to implicate eddy currents correctly by any means. Therefore, I had to choose another way of losses estimation (also discussed in following text).

2. FEM MODEL

A 2D FEM model of the machine investigated so far is set up in order to conduct nonlinear electromagnetic analyze. Fig. 1 shows the geometry of the machine under investigation (without the housing), the mesh of such physical model can be seen in fig 2. The geometry of a machine consists of the stator with double layer windings embedded in open slots. The rotor is manufactured from copper alloy bars interconnected outside the rotor stack. Material properties building up whole model can be seen in following table.

<table>
<thead>
<tr>
<th>Material</th>
<th>permeability [Hm⁻¹]</th>
<th>Resistivity[Ωm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron core</td>
<td>B-H curve</td>
<td>/</td>
</tr>
<tr>
<td>Windings</td>
<td>1</td>
<td>1.78e-8</td>
</tr>
<tr>
<td>Air</td>
<td>1</td>
<td>/</td>
</tr>
</tbody>
</table>

For mesh the quadratic element PLANE53 has been used. It is defined by 8 nodes and has up to 4 degrees of freedom per node: z component of the magnetic vector potential (AZ), time-integrated electric scalar potential (VOLT), electric current (CURR), and electromotive force (EMF). PLANE53 is based on the magnetic vector potential formulation.

3. CALCULATION

The core loss may be evaluated only on the base of known flux distribution in the machine cross section. Fortunately, FEM even in its 2D version, allows us to compute the magnetic field distribution accurately. This may be a strong tool to approximate
the field, especially at high time harmonic frequencies, correctly and quickly.

As I have said before, first we need to obtain is the flux distribution in the machines cross section during common operating state. In order to do that the finite-element solution has been carried out under no-load state (1840 RPM). The model has been loaded (for each harmonic frequency) by a slip frequency for the sake of the reaction of the rotor winding. In this case, the flux is computed accurately.

3.1. Hysteresis and eddy current losses

The hysteresis loop represents energy lost in the core, a kind of magnetic friction, which is additional to an eddy current loss. The area of such loop is a measure of the loss. The loss occurs since the magnetic field reverses direction every one half cycle of the applied voltage, and energy is expended in the core. This loss component is known as a hysteresis loss \( P_H \).

Further, as the magnetic flux reverses its direction and cuts the core structure, induces into magnetic circuit eddy voltage. Because the magnetic material of the machines joke is electrically conductive, the eddy voltage causes creation of eddy currents in here. These currents heat up the core, thus wasting the power. As it was said before, this sort of energy lost cannot be computed by means of FEM directly. Fortunately, there is another way to make this calculation possible. Through empirical curve fitting and research has been found losses to be given by the

\[
\Delta P_{FEM} = \Delta p \left( \frac{f}{50} \right) B^2 m_i [W] \tag{3.1}
\]

\( \Delta p \) ... specific losses of used iron [\( W \cdot kg^{-1} \)]

\( B \) ... flux density at certain element [\( T \)]

\( f \) ... stator/rotor frequency

\( m_i \) ... weight of certain element

The steel's properties can be overviewed synoptically in following table

<table>
<thead>
<tr>
<th>Steel</th>
<th>1.5T</th>
<th>1T</th>
<th>( \rho ) [kg \cdot m^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F350T50</td>
<td>3.5</td>
<td>1.5</td>
<td>7650</td>
</tr>
</tbody>
</table>

Losses arising from changing flux densities in both rotor and stator have a different intensity from each other. Due to low rotor frequency the energy dissipated in here can be considered to be negligible. The picture describes ratio between stator and rotor losses respectively.

3.2. Additional losses

In general, the discontinuities in flux carrying components such as rotor/stator teeth and slots cause the stator rotating field produces loss in both the stator and rotor laminations due to flux pulsations in here. In essence, the total flux in a stator and rotor teeth varies with rotor position due to stator and rotor slot openings. In order to determine these losses we first need to find the amplitude of flux pulsating in stator/rotor teeth. The three 2D models have been used for this purpose. The dimensions of model's geometry
remain the same for each model. Only one parameter has been changed, namely angular displacement of rotor against stator. Thanks to these modifications it is possible to obtain the change of the flux density in teeth as dependent on reluctance varying. The first model considers the teeth synchronized in position with minimum reluctance. The second one stands for the rotor shifted about one half of stator slot pitch ($t_{ds}$). And the third position of the rotor is such that reluctance of magnetic path respective the same rotor tooth is on its maximum.

$$t_{ds} = \frac{\pi D}{Q_1}$$

(3.2)

The amplitude of flux pulsating is calculated as a difference of average flux value for the same tooth through both models. For this case the amplitudes are:

$$B_{stat} = 0.07 \text{T}$$

$$B_{rot} = 0.12 \text{T}$$

Now, it is possible to evaluate (as a matter of fact, it should be said estimate) the additional losses by means of following equitation:

$$\Delta P_{p1} \approx 0.11 \left( \frac{Q_n}{1000} B_{p1} \right)^2 m_{z1}[w]$$

(3.3)

$$\Delta P_{p2} \approx 0.11 \left( \frac{Q_n}{1000} B_{p2} \right)^2 m_{z2}[w]$$

(3.4)

$m_{z} \ldots$ weight of certain element

$Q \ldots$ number of slots

$n \ldots$ RPM

$B_{p} = B_{stat/rot} B_{av}$

3.3. **Surface core losses**

Generally, this sort of loss arises in surface layer of rotor/stator teeth due to air gap flux pulsation. To determine these losses per unit area, first we have to determine the amplitude of such pulsations caused mainly by slots opening. From the FEM model the flux density distribution in air gap can be simply derived (see FIG. 10). The amplitude of pulsation is supposed to be calculated as an average value of flicker superimposed on fundamental flux wave. The value we assess has deep impact to results accuracy (it has to be considered). Now, the rotor and stator surface losses can be calculated from:

$$p_{\Phi 1} = 0.5 k_{01} \left( \frac{Q_n}{10000} \right)^{1.5} \left( B_{01} t_{d1} 10^4 \right)^2 [Wm^{-2}]$$

(3.5)

$$k_{01.2} \ldots$$ factor considering degree of manufacturing

$Q \ldots$ number of slots

$n \ldots$ RPM

$B_{01.2} \ldots$ amplitude of air gap flux pulsation

$t_{d1.2} \ldots$ pole pitch

$$p_{\Phi 2} = 0.5 k_{02} \left( \frac{Q_n}{10000} \right)^{1.5} \left( B_{02} t_{d1} 10^4 \right)^2 [Wm^{-2}]$$

(3.6)

3.4. **Losses caused by time harmonics**

The investigation in such sort of losses we do it in the same way as in the case of iron core losses. Due to the rotor winding reaction the other losses mentioned above can be considered to be negligible. In order to obtain significant harmonics and their amplitudes, we first need to apply the fast Fourier transformation on know PWM of supplying voltage waveform. The currents relevant to these magnitudes could be derived from equivalent circuit of that machine. Each magnitude discussed here is used as a load for an electromagnetic analysis respectively.
The further computation is analogous to previous one relating to the iron core losses estimation. In this case we have to make seven independent analyses whose results can be superimposed.

4. RESULTS

The 1600 kW induction machine under double wye connection has been tested at no-load. The Data have been obtained from the producer’s measurement. In the motor documentation it is pointed out, that the total iron losses are 35626.78[W]

According to (3.1) mentioned above it can be found, that

\[ \Delta P_{FEH,stat} = 15213[W] \]
\[ \Delta P_{FEH,rot} = 9[W] \]

The additional losses have been calculated using (3.3, 4):

\[ \Delta P_{p1} = 2123[W] \]
\[ \Delta P_{p2} = 5263[W] \]

The surface core losses are determined by (3.5, 6):

\[ \Delta P_{s1} = 1852[W] \]
\[ \Delta P_{s2} = 3172[W] \]

The higher time harmonics generate very small partition of total iron losses. It is caused by very low current creating the electromagnetic field in the machines yoke. This exciting rate cannot make it possible to saturate the yoke at its nominal value. The flux density is therefore very low by way of resulting losses.

\[ \Delta P_{FE,f2} = 0.184[W] \]
\[ \Delta P_{FE,f3} = 0.055[W] \]
\[ \Delta P_{FE,f4} = 0.124[W] \]
\[ \Delta P_{FE,f5} = 0.8[W] \]
\[ \Delta P_{FE,f6} = 0.34[W] \]
\[ \Delta P_{FE,f7} = 0.3[W] \]

Now it is possible to say that iron core losses caused by time harmonics can be considered to be omitted.

The total iron losses are calculated:

\[ \Delta P_{IRON, CORE} = \Delta P_{FEH} + \Delta P_p + \Delta P_s = 27632[W] \]

difference: \[ \delta = \left(1 - \frac{27632}{35627}\right) \times 100 = 22\% \]
5. CONCLUSION
A simple algorithm for predicting the iron losses in a squirrel-cage induction motor has been proposed. The flux density distribution (needed for calculated) in the cross section of the motor is calculated by means of FEM. The method presented in this paper has produced losses that are 22 percent less than measured losses. This inaccuracy may be caused by asymmetries in the core manufacturing, poor accuracy of pre-set in material model settings (iron nonlinearity, resistivity ...), etc. Every step of postprocessing calculation has been done through the use of a proper APDL script.

6. BIBLIOGRAPHY
[1] Szabó, L; Dobaik, K; Fodor, D; Tóth,F.: Study on squirrel cage faults of induction machines by means of advanced FEM based simulation – paper of EDPE 2005, Technical University of Cluj, University of Veszprém, University of Miskolc
[5] Tarvydas, P, Edge Elements for 3D Electromagnetic Filed Modeling, Kaunas University of Technology, ISSN 1392 - 1215

Author:
Ing. Vladimir Kindl
University of West Bohemia in Pilsen
str. Univerzitni 26
306 14 Pilsen
tel. (+420) 37763 4454
email: vkindl@kev.zcu.cz