ELECTRICAL ENGINEERING

Toward including the effect of manufacturing processes in the pre-estimated losses of the switched reluctance motor

Eyhab El-Kharahi a,*, Maher El-Dessouki a, Pia Lindh b, J. Pyrhönen b

a 1 El-Sarayat Street, Abdou Basha Square, Abbassia, 11517, Faculty of Engineering, Electrical Power & Machines Department, Ain Shams University, Cairo, Egypt
b Department of Electrical Engineering in LUT Energy, Lappeenranta, Finland

Received 28 June 2014; revised 27 August 2014; accepted 9 September 2014

KEYWORDS
Iron losses; Manufacturing effect; Adaptive finite element; Matlab/Simulink; High non-linear machine; Steinmetz formulas

Abstract The estimation of losses plays a key role in the process of building any electrical machine. How to estimate those losses while designing any machine; by obtaining the characteristic of the electrical steel from the catalogue and calculate the losses. However, this way is inaccurate since the electrical steel performs several manufacturing processes during the process of building any machine, which affects directly the magnetic property of the electrical steel and accordingly the characteristic of the electrical steel will be affected. That means the B–H curve of the steel that was obtained from the catalogue will be changed. Moreover, during loading and rotating the machine, some important changes occur to the B–H characteristic of the electrical steel such as the stress on the laminated iron. Accordingly, the pre-estimated losses are completely far from the actual losses because they were estimated based on the data of the electrical steel obtained from the catalogue. So in order to estimate the losses precisely significant factors of the manufacturing processes must be included. The paper introduces the systematic estimation of the losses including the effect of one of the manufacturing factors. Similarly, any other manufacturing factor can be included in the pre-designed losses estimations.

© 2014 Production and hosting by Elsevier B.V. on behalf of Ain Shams University.

1. Introduction

Theoretically, the foundation of any design of any electrical machine, and how to calculate its losses estimation is based on the characteristic of the unprocessed electrical steel that is obtained from the catalogue without including the effect of manufacturing processes [1]. The previous researches found out that the process of including the effect of manufacturing processes on the steel through the pre-designed loss estimation
was somehow difficult, and needs a thorough understanding, which complicate the process of loss estimation. That discouraged the machine designers to include these effects in the pre-estimated losses of the electrical machine [1]. For further clarification, the process of designing and building any electrical machines has different aspects such as magnetic circuit, the electrical circuit, the thermal design, the mechanical design, the ventilations, the isolation, the bearing, and the balancing of electrical and mechanical circuits. All those different aspects are related to the design and the building of any electrical machine. Moreover, the machine frequently needs a controller or a sensor. Those factors are more than enough to complicate the process of designing and building electrical machine. However, the manufacturing processes have great impacts on the unprocessed electrical steel and these impacts must be included in the design and pre-estimated losses of the electrical machine [2].

From this point of view, the paper addresses a simple approach to include the manufacturing factors in the design and pre-estimated losses. Since the manufacturing processes affect the B–H characteristic of the electrical steel, which means that if the effect of any manufacturing process on the electrical steel is known through the experiences or previous measurements, then a mathematical formula can be concluded to the relation between the manufacturing process and the flux density to create a new B–H curve of the electrical steel. In other words, the B–H curve of the electrical steel, which is obtained from the catalogue, is now modified according to this mathematical formula, which link between the flux density and the manufacturing factor. Now a new B–H curve can be used in the pre-design process and in the loss estimation without the miscalculation in the previous steps [3].

This paper explains in detail the design and losses estimation process, using an example of an electrical machine with non-linear characteristic and rotational transient operation. This means that this electrical machine has no steady state operation, which means that it has high iron losses. The objective of doing that was to illustrate in detail how the calculation of the iron losses is determined by including a manufacturing factor by simple steps [4].

2. Understanding one of the manufacturing effects in the electrical machine

The manufacturing process of the electrical steel sheet causes distortion, residual stress, etc. in the electrical steel sheet. The distortion and the residual stress of the electrical steel sheet used in the stator and the rotor are the causes of the iron loss increment, which also generates the degradation of the magnetic properties of a magnetic circuit of the machine that built from punched electrical steel sheets [5].

Punching the iron sheets affects the material properties and creates heterogeneous stress inside the sheets. The effect is depending on the alloy composite, whereas the grain size in the sheets seems to be the main influencing factor, especially for operating ranges between 0.4 T and 1.5 T. The influenced region in the sheet due to cutting and punching goes up to 10 mm in distance from the cutting edge, where the permeability is significantly decreased. This reduction in permeability increases the iron losses in the material. Specifically, for geometric parts smaller than 10 mm in width (small stator teeth for example), the punching process can have a significant influence on the iron losses and therefore has to be considered in the loss calculation. Further, the cutting and punching process damages the thin insulation layer. This might lead to have short circuits between several sheet layers. In this paper, the punching effect will be included in the pre-designed losses estimation [5].

3. The proposed electrical machines for design and losses estimation including one of the manufacturing factors

This paper will use the switched reluctance motor as an example for non-linear electrical machines that has a core exposed and all its running time in non-sinusoidal excitation. The switched reluctance motor estimation losses will be illustrated in detail within this paper, using the punching effect as the manufacturing process factor in the losses estimation process [6].

The losses in the switched reluctance motor (SRM) consist mainly of the stator copper losses and the core losses. The copper losses are proportional to the square of the root mean square of the current whereas the core losses are a function of the excitation frequency and the flux density. The iron losses in the SRM cannot be ignored as the SRM always operates in transient operation mode. During transient operations, the high switching frequency increases the iron loss to a significant value compared with the value of copper loss [6].

The process of concluding the SRM iron losses value is complicated, because the frequency of the varying of the flux reversals depends on the place and time. Therefore, the iron losses are different for each part of the motor’s cross-sectional area. In addition, the iron losses depend on the flux density, whose waveform varies in different zones of the SRM. Moreover, the current waveforms are non-sinusoidal and they depend on the operating conditions and the type of controller. These factors have significant impact on complicating the process of the estimation of the core losses [7].

The models for the iron losses estimation either can be empirical or based on the solution of Maxwell’s equations. The general idea for finding any formula to estimate the iron losses in the SRM is based on separating the specific core losses (W/kg) into three parts (hysteresis, eddy current and excess losses) and to be calculated using the waveforms and time derivatives of the local flux densities.

The equation for estimating the iron losses [7]:

\[ P_{\text{iron losses}} = P_{\text{hysteresis}} + P_{\text{eddy}} + P_{\text{anomalous}} \]  

(1)

4. Design of the SRM in case of excitation by non-sinusoidal excitation

The output torque of any electric machine can be calculated by three different variables. The variables are the air gap flux density \( B \), the machine volume \( V \), and a constant \( C \) as follows:

\[ T = C \cdot B \cdot V \]  

(2)

This method usually used in case of designing electrical machines that have linear characteristics. However, this method cannot be used for designing any highly non-linear characteristic electrical machines, because this method function depends on the assumptions of ratios and many
approximations in the magnetic circuit and the winding configurations. The switched reluctance motor SRM is a device with double rotational salient pole with single excitation that usually works fully saturated. The torque here resulted by the switched reluctance motor’s rotor tendency to move to a position where the maximisation of inductance of the excited phase winding occurs. Therefore, there is a need to have a power converter with solid-state to generate the right sequence of phase commutation according to the position of the rotor. The curves that represent flux linkage with consideration of current and rotor position, \( \Psi(\theta, i) \), are called magnetisation curves, and they are a key point for the SRM. Then due to the combined effects of saturation, saliency and hysteresis, these curves found to be very difficult to determine with any degree of precision using the relationships methods derived from SRM geometry. Therefore, their accurate determination requires adaptive finite element (FE) calculations [8].

5. Using the adaptive two dimensions finite element to design 12/8 SRM

Fig. 1 illustrates a schematic diagram of the proposed 12/8 three phases SRM. The figure illustrates the machine magnetic circuit layout in boundary conditions.

Fig. 2 illustrates the initial finite element mesh of the machine.

The first step in the finite element process is to generate a set of machine parts to define the geometry as shown in Fig. 2. These objects are defined by co-ordinate pairs, taken in counter-clockwise order, defining successive vertices of polygonal figure defining the component. In this case, there are five parts: the stator, the air gap, the two conductors, and the rotor. Dividing the machine parts into those five parts illustrates the layout of the machine in flat 2D layout, which means that the curved surfaces of the machines are represented as a series of straight lines; therefore, the use of sufficient meeting points is necessary especially in the important air gap areas. From this definition of the machine part, emerge the initial mesh [9].

The geometry and the layout of the machine are known from the design synthesis stage, and consequently, the information required defining the iron saturation curves, conductor positions, and boundary conditions. The task is merely to map this information onto the initial finite element mesh.

In the third step, the initial mesh is adapted for further accuracy, Fig. 3.

Fig. 3 shows the mesh after adaptation in the motor as shown in Fig. 1 and it is clear that the meshes fit with all the parts especially the small parts that cannot be modelled mathematically.

6. Electric circuit design, performance optimisation and losses computation in 12/8 standard SRM

The second part of designing the conventional 12/8 SRM is to design the electric circuit. The design of any electric circuit has to include the following three factors (the determination of the best number of the turns, the cross-sectional area of the conductor and the number of the coils). The following step after the design of this motor is the performance optimisation. The performance optimisation is applied through two phases: The First phase, by selecting different values of the intervals between switching on/off angles, and the second phase by changing the switching on angles. The best values are the values that lead to maximising the torque. This process may lead
to increasing the value of the current density in the conductor; the reason is that the number of turns was kept in constant pace. Thereby a current limiter has been used while operating this machine. But in the case of calculating the losses the angles have to be chosen under the current density condition $J \leq 10 \, \text{A/mm}^2$. The next step after designing and performance optimisation is to calculate the losses conclude the efficiency analysis [10].

Fig. 4 illustrates the conventional SRM $t_s = t_r$ and $t_s/t_r = 0.33$ meaning that the stator and rotor poles have equal widths.

$$\dot{\psi} = U_{dc} \cdot t_m = 560 \cdot 1.667 \cdot 10^{-3} = 0.93352 \, \text{V} \cdot \text{s}$$

Figs. 5 and 6 show the flux and torque of the machine versus current and rotor position.

7. Modelling the SRM in Matlab/Simulink

The machine performance has been calculated in an analytical manner by using the fundamental equation of the terminal voltage of any machine:

$$u = R \cdot i + \frac{\partial \psi}{\partial t}$$

(3)

A numerical approach to the simulation of SRMs has been introduced in [11,12]. The flux-linkage can be determined from this equation:

$$\psi = \int \left( v - R \cdot i(\theta, \psi) \right) \, dt$$

(4)

The torque can be obtained indirectly from the magnetic circuit co-energy:

$$W(\theta, i) = \int_0^1 \psi(\theta, i) \, di \bigg|_{i=const}$$

(5)

$$T(\theta, i) = \frac{dW(\theta, i)}{d\theta} \bigg|_{i=const}$$

(6)

Fig. 7 shows the block diagram of the SRM simulation package. The flux linkage characteristic data are taken from an adaptive finite element solution of the magnetic characteristics. It is stored in tables (one for the flux-linkage characteristic and one for the torque), then loaded into a simulation of the SRM using Matlab/Simulink. Fig. 8 illustrates the current waveforms when the torque is rated and square voltage pulses.
$I_{\text{rms}} = 5.7 \text{ A (on/off angles: } 0/15 \text{ mech. degrees)}$

$J_{\text{rms}} = \frac{I_{\text{rms}}}{\text{ Area of one conductor }} = \frac{5.7}{0.5733} \approx 10 \text{ A/mm}^2$

**Fig. 9** illustrates total torque waveform when the machine is driven by the simple voltage pulses that is illustrated in **Fig. 10** to produce the flux-linkage waveform versus position that is illustrated in **Figs. 11 and 12**.
7.1. The flux waveforms

In the SRM, the flux density waveforms are non-sinusoidal, and then we find that the waveforms change according to which part of the magnetic circuit it occurs. The flux densities in the different parts of the SRM are deducted from the flux density of the stator poles. Flux density waveforms of the stator poles are more or less unipolar triangular pulses and depend on three factors (the phase switch conducting period, the diode conducting period and, of course, the type of control). The flux densities of all stator phases have the same waveform, albeit shifted by the delay angle. The different flux waveforms in the stator yoke are obtained by summing the stator pole flux waveforms in the different zones of the magnetic circuit. The flux polarity in the rotor reverses at every half a revolution, so the rotor poles flux waveforms are bipolar. The rotor yoke flux waveform is obtained by subtracting the rotor pole flux waveforms. Fig. 13 illustrates the flux densities in the three stator poles.

The flux densities in the stator yokes are calculated from the flux density in the stator poles illustrated in Fig. 14:

\[ B_{s y1} = B_{sp2} + B_{sp1} - B_{sp3} \]
\[ B_{s y2} = B_{sp1} - B_{sp2} - B_{sp3} \]
\[ B_{s y3} = B_{sp1} + B_{sp3} - B_{sp3} \]  

(7)

From the distribution of the flux inside the machine which is illustrated in Fig. 4(a) the flux can be determined in the different parts of the rotor. Then dividing it by the area of each zone, the flux densities can be determined and they are illustrated in Figs. 15 and 16.

\[ B_{r y1} = \hat{B}_{ry1} \]
\[ B_{r y2} = \hat{B}_{ry2} \]
\[ B_{r y3} = \hat{B}_{ry3} \]  

(8)
8. Losses in the SRM

The flow chart in Fig. 17 summarises the steps in this paper to estimate the losses in the SRM.

8.1. Predicting the iron losses using Steinmetz formula [13–15]

(a) Calculation of the hysteresis losses.

\[ P_{h} = k_{n}^{h} \cdot f \cdot \hat{B}^{x} \quad (9) \]

where \( k_{n}^{h} = 2.01 \cdot 10^{-2} \), \( x = 1.84 \).

The Steinmetz constant \( x \) and \( k_{n}^{h} \) are dependent on the lamination material.

(b) The equation for calculating the eddy current losses in the SRM.

\[ P_{e} = \frac{k_{n}^{e}}{\sqrt{2 \cdot \pi}} \cdot \left( \frac{d\hat{B}}{dt} \right)^{2} \quad (10) \]

\[ P_{e} = 3.75 \cdot 10^{-5} \cdot \left( \frac{d\hat{B}}{dt} \right)^{2} \]

(c) Calculation of the anomalous losses for the machine performed by using the following formula.

\[ P_{a} = k_{n}^{a} \cdot \left| \frac{d\hat{B}}{dt} \right|^{1.5} \quad (11) \]

where \( k_{n}^{a} = 3.43 \cdot 10^{-4} \).

8.2. Calculation of the copper losses

Fig. 18 shows one stator tooth and four stator slots. There are four coils per phase. Each coil fills two halves of two stator slots, as shown above:

The circumferential length of the section shown (\( y \)) from the end-winding turns is estimated as follows [29–32]:

1. The length is taken as average distance from the centre of the windings of the coil on the right side of the tooth to the centre of the windings of the coil on the left side of the tooth.
2. \( R_{st\_inner} \) is the inner radius of the stator, \( L_{ps} \) is the stator tooth height and \( t \) is the stator tooth width.
3. The mean circumferential distance for one end-winding arc = \( (2\pi/12) \cdot (R_{st\_inner} + L_{ps}/2) \). Subtracting the stator tooth width from this value approximately gives the mean circumferential length between winding centres.

\[ y = \frac{\left(2\pi(R_{st\_inner} + L_{ps}/2)/12 - t\right)}{2} + t = 0.0209 \text{ m} \]

Total length of one turn = \( 2 \cdot 0.15 + 2 \cdot (1.5'0.01176) \)
\[ + 2 \cdot 0.0209 = 0.38 \text{ m} \]

Copper loss for 3-phase

\[ P_{loss} = 3J^{2}pV_{cu} \]

\[ = 3 \cdot (10^{-6})^{2} \cdot 0.0178 \cdot 10^{-6} \cdot 300 \cdot 0.37708 \cdot 1.1466 \cdot 10^{-6} \]
\[ = 692.64 \text{ W} \]

Figure 17 Flowchart of core losses calculation process.

Figure 18 One stator tooth and two stator slots.

Figure 19 Distribution of the losses in the different parts of the SRM.
Fig. 19 illustrates the distribution of the losses in the different parts of the SRM as a percentage of total losses.

Fig. 20 illustrates the percentage of the copper losses, anomalous losses, hysteresis losses and eddy current losses as a percentage of the total losses.

Total losses = Copper Losses + Iron Losses = 818.09 W

Input Power = 3 × 560 × 5.7 = 9576 W

Efficiency = $100 \times \left[ (9576 - 818.09)/9576 \right] = 91.456\%$

9. Including the manufacturing effect in the losses calculations

The mathematical formula in [5] is used to include the effect of punching the electrical steel in the losses estimation of the SRM:

$$B_{\text{old}} = \frac{k}{1 - e^{-k}} B_{\text{new}}$$  \hspace{1cm} (12)

where $k$ in Eq. (4) is the manufacturing factor (see Tables 1 and 2).

Tables 3–6 resulted from applying Eq. (12) to find the flux density in different parts of the magnetic circuit:

---

**Table 1** Machine parameters for a 12/8 SRM.

<table>
<thead>
<tr>
<th>Value</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (rpm)</td>
<td>1500</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>200</td>
</tr>
<tr>
<td>The number of conductors per phase</td>
<td>300</td>
</tr>
<tr>
<td>Copper fill factor</td>
<td>0.4</td>
</tr>
<tr>
<td>DC voltage (V)</td>
<td>560</td>
</tr>
</tbody>
</table>

**Table 2** Volume, hysteresis loss and anomalous loss of the different parts of the core of the 12/8 SRM.

<table>
<thead>
<tr>
<th>Volume (m$^3$)</th>
<th>Hysteresis losses (W)</th>
<th>Anomalous losses (W)</th>
<th>Eddy current losses (W)</th>
<th>Iron losses (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator poles</td>
<td>5.0 × 10$^{-4}$</td>
<td>42</td>
<td>3.4</td>
<td>5.4</td>
</tr>
<tr>
<td>Stator yoke</td>
<td>4.0 × 10$^{-4}$</td>
<td>35</td>
<td>7.8</td>
<td>17.3</td>
</tr>
<tr>
<td>Rotor poles</td>
<td>2.3 × 10$^{-4}$</td>
<td>6</td>
<td>0.92</td>
<td>1.05</td>
</tr>
<tr>
<td>Rotor yoke</td>
<td>1.4 × 10$^{-4}$</td>
<td>4</td>
<td>1.07</td>
<td>1.7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3** $B_{\text{old}}$ (stator poles).

<table>
<thead>
<tr>
<th>$k$</th>
<th>0.01</th>
<th>0.03</th>
<th>0.06</th>
<th>0.1</th>
<th>0.13</th>
<th>0.17</th>
<th>0.2</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{old}}$</td>
<td>1.7085</td>
<td>1.7256</td>
<td>1.7515</td>
<td>1.7864</td>
<td>1.81289</td>
<td>1.84859</td>
<td>1.87566</td>
<td>2.16</td>
<td>2.689</td>
</tr>
</tbody>
</table>

**Table 4** $B_{\text{old}}$ (stator yoke).

<table>
<thead>
<tr>
<th>$k$</th>
<th>0.01</th>
<th>0.03</th>
<th>0.06</th>
<th>0.1</th>
<th>0.13</th>
<th>0.17</th>
<th>0.2</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{old}}$</td>
<td>1.73</td>
<td>1.7479</td>
<td>1.774166</td>
<td>1.8095</td>
<td>1.836</td>
<td>1.8725</td>
<td>1.899</td>
<td>2.1879</td>
<td>2.723</td>
</tr>
</tbody>
</table>

**Table 5** $B_{\text{old}}$ (rotor poles).

<table>
<thead>
<tr>
<th>$k$</th>
<th>0.01</th>
<th>0.03</th>
<th>0.06</th>
<th>0.1</th>
<th>0.13</th>
<th>0.17</th>
<th>0.2</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{old}}$</td>
<td>0.89</td>
<td>0.899</td>
<td>0.91253</td>
<td>0.9307</td>
<td>0.9445</td>
<td>0.96311</td>
<td>0.9772</td>
<td>1.12536</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**Table 6** $B_{\text{old}}$ (rotor yoke).

<table>
<thead>
<tr>
<th>$k$</th>
<th>0.01</th>
<th>0.03</th>
<th>0.06</th>
<th>0.1</th>
<th>0.13</th>
<th>0.17</th>
<th>0.2</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{old}}$</td>
<td>0.9246</td>
<td>0.93385</td>
<td>0.94787</td>
<td>0.9667</td>
<td>0.981</td>
<td>1</td>
<td>1.015</td>
<td>1.1689</td>
<td>1.455</td>
</tr>
</tbody>
</table>

Please cite this article in press as: El-Kharahi E et al., Toward including the effect of manufacturing processes in the pre-estimated losses of the switched reluctance motor, Ain Shams Eng J (2014), http://dx.doi.org/10.1016/j.asej.2014.09.005
Figure 21 Flux density in different parts of the core of the SRM before any iron manufacturing process versus manufacture factor.

Figure 22 Impact of the manufacturing factor on the hysteresis losses.

Figure 23 Impact of the manufacturing factor on the anomalous losses.

Figure 24 Impact of the manufacturing factor on the eddy current losses.

Figure 25 Impact of the manufacturing factor on the different types of the iron losses.

Figure 26 Distribution of the iron losses in different parts of the core.
10. Conclusion

The paper clarifies the misconception of the losses estimation in any electrical machine, in case of the manufacturing effects are not included in the loss estimation. Moreover, that loss estimation must be modified to include the manufacturing factors when it is based on the unprocessed electrical steel. In addition, the paper highlights two main factors regarding the manufacturing effect, first it has to be simplified to avoid the complicating the design and building process the electrical machine. Second, it has to be included in the iron losses estimation.

The paper explains the iron losses estimation in nonlinear electrical machine using the switched reluctance motor (SRM) as an example. The paper started with a detailed explanation of the design of the magnetic circuit and the electrical circuit and then obtaining the flux density waveforms in different zones. The paper proceeds to present the estimation of the losses using Steinmetz formula and the modifications of the flux density according to the manufacturing effect. Concluding that the efficiency decreases as the manufacturing factor increases.

Appendix A

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRM</td>
<td>Switched reluctance motor</td>
</tr>
<tr>
<td>12/8</td>
<td>12 poles in the stator and 8 poles in the rotor</td>
</tr>
<tr>
<td>Udc</td>
<td>Converter DC supply voltage</td>
</tr>
<tr>
<td>t_on</td>
<td>Switching on time</td>
</tr>
<tr>
<td>W^c</td>
<td>Co-energy</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>θ</td>
<td>Rotor position</td>
</tr>
<tr>
<td>t_s</td>
<td>Stator tooth width</td>
</tr>
<tr>
<td>t_r</td>
<td>Rotor tooth width</td>
</tr>
<tr>
<td>I</td>
<td>Current</td>
</tr>
<tr>
<td>I rms</td>
<td>Root mean square value of the current</td>
</tr>
<tr>
<td>J</td>
<td>Current density</td>
</tr>
<tr>
<td>J rms</td>
<td>Root mean square value of the current density</td>
</tr>
<tr>
<td>Ψ</td>
<td>Flux linkage</td>
</tr>
<tr>
<td>Ψ max</td>
<td>Maximum flux density</td>
</tr>
<tr>
<td>Φ</td>
<td>Flux</td>
</tr>
<tr>
<td>Β max</td>
<td>Maximum flux density</td>
</tr>
<tr>
<td>Β sp</td>
<td>Flux density in the stator yoke</td>
</tr>
<tr>
<td>Β rp</td>
<td>Flux density in the stator pole</td>
</tr>
<tr>
<td>λ r</td>
<td>Rotor pole pitch = Rotor diameter/number of rotor poles</td>
</tr>
<tr>
<td>ρ</td>
<td>Resistivity of copper</td>
</tr>
<tr>
<td>V_cu</td>
<td>The volume of the copper in the stator of the machine</td>
</tr>
<tr>
<td>T_s</td>
<td>Is the specific loss (W/m³)</td>
</tr>
<tr>
<td>P iron losses</td>
<td>Total iron losses</td>
</tr>
<tr>
<td>P hysteresis</td>
<td>Hysteresis losses</td>
</tr>
<tr>
<td>P eddy</td>
<td>Eddy current losses</td>
</tr>
<tr>
<td>P anomalous</td>
<td>Anomalous losses</td>
</tr>
<tr>
<td>B sp</td>
<td>Flux density in the stator pole</td>
</tr>
<tr>
<td>B sy</td>
<td>Flux density in the stator yoke</td>
</tr>
<tr>
<td>B rp</td>
<td>Flux density in the rotor pole</td>
</tr>
<tr>
<td>B ry</td>
<td>Flux density in the rotor yoke</td>
</tr>
<tr>
<td>P copper losses</td>
<td>Copper losses</td>
</tr>
</tbody>
</table>

References

The effect of manufacturing in the design and losses estimation of the reluctance motor


Please cite this article in press as: El-Kharahi E et al., Toward including the effect of manufacturing processes in the pre-estimated losses of the switched reluctance motor, Ain Shams Eng J (2014), http://dx.doi.org/10.1016/j.asej.2014.09.005