Design approach of squirrel cage induction motors by use of an iron loss optimisation method for improving efficiency

B. B. Saanane, A. H. Nzali & D. J. Chambega
Department of Electrical Power Engineering,
University of Dares Salaam, Tanzania

Abstract

The design of electrical machines presents a mathematically indeterminate problem. There is no single optimum design and to compound the problem there are different ways to solve a design problem in electrical machines. A substantial part of the losses in electric machines is the loss in the iron core, and so, through optimisation, the motor efficiency can still be improved. In this paper, an iron loss prediction model is developed which ensures a minimized iron loss for any standard motor frame. Through the generated optimal points of stator bore diameter, $D$, and air-gap magnetic flux density, $B$, a new motor geometry is reconfigured which assures lowered iron and total motor losses. The new motor design was simulated on a 2D-FEM to analyse the new motor response. Experimental results, which agree with the results of the design, show an improvement of motor efficiency. Empirical formulae are also developed which can greatly assist motor designers.

Keywords: iron loss model, optimisation, analysis, design formulae, efficiency.

1 Introduction

Computation of iron (core) losses in induction motors cannot be performed through exact analytical methods but is dependent mainly on empirical constants and experience of motor designers and manufacturers. In comparison to copper losses which are to a larger extent easier to calculate, iron losses are mostly associated with some practical quantities, for example the type of material and manufacturing conditions.
2 Iron loss prediction model

The optimisation was carried out through this model incorporating also, the complete stator and rotor geometry. This model was then implemented on a MATLAB 6.5 platform.

2.1 Assumptions for the approximate iron loss prediction model

Prediction and subsequent optimisation of iron loss was achieved by minimizing the losses in different sections of the core through minimization of their magnetic flux densities by influencing on the air gap flux density. The limit of the air gap flux density $B$ for a given maximum induction in the stator and rotor teeth and backs, depended on the thickness of the teeth and the backs.

Also, during the process of energy transformations in induction machines, several undesirable effects are generated, like heating, as a result of energy losses; noise from radial magnetic forces and cooling fans; vibrations etc. These effects are generally referred to as parasitic effects. In this model, these parasitic effects were not considered, with the exception of the surface and teeth reluctance losses in the rotor.

Hence, for a given motor geometry and by varying the air gap induction $B$ and air gap diameter $D$, the iron loss prediction model was developed with consideration of the following assumptions: (1) The non-linear magnetic behavior of the iron material was taken into consideration by allocating a maximum flux density in different iron regions of the machine; (2) The leakage fluxes in the air gap and slots were neglected, such that, all magnetic flux crossing the air gap was assumed to flow radially through the teeth; (3) The overhang effects were neglected, that is, only the active region within the laminations was considered in the optimization; (4) Stray losses were not included in the model; (5) A sinusoidally distributed air gap flux density was assumed; and (6) The current loadings in the stator and rotor were determined by the cooling capacity and the available slot areas in the motor cross-section.

2.2 Optimisation of iron loss prediction model

In this approximate iron loss prediction model, optimization of iron loss was achieved by minimizing the losses in different sections of the core by influencing the airgap flux density $B_\delta$ and air gap diameter $D$. The limit of the air gap induction $B_\delta$ for a given maximum induction in the stator and rotor teeth and back depended on the thickness of the teeth $bts$, $btr$ and backs $hrs$, $hrr$. These geometrical dimensions depended also on the airgap diameter $D$. Therefore, by
increasing $B_\delta$ the available space areas for slots $A_{ss}$, $A_{sr}$ decreased and as a consequence also, the current loadings $S_{ss}$, $S_{sr}$ decreased. Conversely, by increasing the current loadings, brought about an increase in the slot areas and a reduction in the widths of the teeth and the backs. As a result, the airgap induction $B_\delta$ decreased.

![Flowchart](image)

Figure 1: Flowchart of optimisation for the iron loss prediction model.
Compute stator and rotor winding copper loss: $P_{sw}, P_{rw}, P_{cu}(n,m) = P_{sw} + P_{rw}$

Compute maximum torque, $\text{maxTq}(n,m)$

$maxTq(n,m) > \text{Tr}$

Yes

Compute Iron loss components in the stator and rotor: $P_{fet}, P_{fer}, P_{tar}, P_{ytr}$ and $P_{exc}$: $P_{fe} = P_{fet} + P_{fer} + P_{tar} + P_{ytr} + P_{exc}$

$Tq(n,m) = \text{Tr}$

No

$Tq(n,m) = \text{Tr}$ and modulus $P_{cu}(n,m)$

Yes

Minimize sum, $\text{min}(P_{fe}(n,m) + P_{cu}(n,m))$ as function of $D$ and $B$

3-D plot, $P_{fe}(B,D)$ and $\text{minPfe}$

Get optD and optB from $\text{minPfe}(n,m)$

Compute new geometry for stator and rotor with optD and optB for $\text{minPfe}$

END

Figure 1: Continued.
With what is stated above, it was important to consider in the beginning, the iron losses together with the copper losses as in a real motor. Thereafter, the iron loss curve as a function of $\delta^B$ and $D$ was minimized, fig.2. But in this model, the motor for every shaft power was dimensioned by maintaining the same nominal (rated) torque, the same outer diameter of the stator core and the same airgap thickness. This was done so in order to keep the same dimensions of motor manufacturers.

Through minimization of $P_{fe}(B, D)$ the optimal point was located and the corresponding values for $B$ and $D$ were determined as opt$B$ and opt$D$. These new values opt$B$ and opt$D$, then facilitated to compute the new motor geometry for stator and rotor cores with reduced iron losses. Implementation of this model was done on the MATLAB 6.5 platform on the basis of the flowchart, fig.1.

2.3 Flowchart of optimisation for approximate iron loss prediction model

The flowchart as shown in fig.1 for the approximate iron loss prediction model was developed on the basis of the motor geometry including the simple thermal model of a motor and the empirical iron loss formulae. The initial conditions were considered to be the nominal values of the original motor frame in this case the ABB motor type M3AP 160 L-4 for 15 kW. The idea therefore, was to try the iron loss optimisation method on this original motor geometry, in order to get a new geometry, which has lowered iron loss and total loss. So, this could lead to
efficiency improvement of the same motor frame size, but with a re-configured geometry. The iteration was conducted on varying the air gap induction, $B_s$, and air gap diameter, $D$ and also through the logic loops for the model to be able to compute the minimized value of iron loss, $P_{fe}(B, D)$, of the motor.

3 Model results

The developed approximate iron loss prediction model was applied to an ABB frame size of a three-phase squirrel cage motor, 15 kW 4-pole. The iron loss correction factors were introduced in the iron loss empirical expressions, in order to account for other loss making mechanisms, like the stray losses which were not included in the model.

This iron loss prediction model was able to give theoretical results as shown in fig.2. and fig.3. From fig.2, it was possible to locate the point with minimum iron loss, $\text{min}P_{fe}$, and the corresponding values, $\text{opt}B$ and $\text{opt}D$. Thereafter, values of randomly selected seventeen options were explored as shown in fig.3, through various combinations of peak values of magnetic flux densities, in different motor sections for both stator and rotor.

![optPfe, [W]](optPfe, [W])

Figure 3: Seventeen options for iron loss optimization on a 15 kW, 160 L-4 motor.

4 Formulation of empirical formulae

The statistical analysis of the model results was performed using a software which employs a large number of regression models (both linear and non-linear) as well as various interpolation schemes to represent data in the most precise and convenient way, Chapra and Canale [2].

With the generated set of model data points, the idea was to find an analytical equation which best agrees with the available data using. Optimally, the model was chosen to reflect that law so that the parameters in the curve fit, gave the
desired physical interpretation and meaning. So, the optimised parameters $B$, $D$, $P_{cu}$ and $P_{fe}$ were then statistically analysed using the software. Around these optimal points, empirical relationships $D(B)$, $P_{fe}(B)$, and $P_{cu}(P_{fe})$ were formulated with the help of the software, as given in eqns.(1), (2) and (3).

4.1 Empirical relationships for the 15 kW motor

Following below are the developed novel empirical formulae:

$$D = a + bB + cB^2 + dB^3,$$

where:

$a = 4.8121051$, $b = -22.112476$, $c = 31.935455$, $d = -18.773035$; $D$ [m] and $B$ [T]. The limits are:

$0.5700 < B < 0.6900$ and $0.1580 < D < 0.1760$ m ·

$$P_{fe} = a + bB + cB^2 + dB^3,$$

where:

$a = 186363.05$, $b = -834456.03$, $c = 1248912.5$, $d = -622984.39$; and $P_{fe}$ [W] and $B$ [T]. The limits are:

$0.6300 < B < 0.6900$ and $539.9300 < P_{fe} < 573.800$ W ·

$$P_{cu} = a + bP_{fe} + cP_{fe}^2 + dP_{fe}^3,$$

where:

$a = -4049416.8$, $b = 22282.868$, $c = -40.851615$, $d = 0.024954481$; and $P_{cu}$ [W] and $P_{fe}$ [W]. The limits are:

$536.1100 < P_{fe} < 546.1500$ W and $382.500 < P_{cu} < 451.5500$ W ·

5 Finite element method analysis of new motor geometry

The evaluation of electromagnetic field in all the FLUX2D version 7.60 simulations was based on the finite element computation of the unknown represented by the magnetic vector potential, a vector normally oriented to the computation domain, Masato and Kenji [3].

5.1 No-load motor operation

Two magneto-harmonic models of no-load operation for rated source voltage and frequency were employed: (1) simulation with a value lower than the rated slip; and (2) simulation with rated slip and with a value of rotor bar resistivity much larger than the real value; a value $10^5$ times greater was used. The two models gave practically the same results as shown in fig.4 and fig.5.

The main numerical results of no-load simulation were: (1) the value of no-load current for each phase was, $I_{10} = 18.7A$, 19A, 20.9A; (2) stator and rotor iron loss was 343 W.
Figure 4: Air gap flux density and the higher harmonics present including the fundamental one.

Figure 5: Chart of magnetic field lines for no-load motor operation.
6 Discussion of results and conclusion

In comparing the analytical model results with the experimental data as shown in Table 1, it is clear that the model gives a lower value of the iron loss and total loss than with the results from the original motor frame. This then allows to improve the motor efficiency, Oriano et al. [4] and Stumberger et al. [5]. Therefore this model and the developed empirical formulae, eqns. (1), (2) and (3) are very easy tools to motor designers.

<table>
<thead>
<tr>
<th>Motor type for ABB frames</th>
<th>Computed data from original geometry</th>
<th>Simulated data for new geometry with developed model</th>
<th>Experimental data on original motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3AP 160 L-4</td>
<td>A) At unity iron loss correction factors: Kbh=1, Kbr=1, Kbr=1 Pcu=346.74 W Pfe=102.95 W Pfe=380.55 W Pfe=118.03 W Pfe=609.29 W Pfe=956.03 W</td>
<td>A) At unity iron loss correction factors: Kbh=1, Kbr=1, Kbr=1 Pcu=383.48 W Pfe=139.06 W Pfe=10.72 W Pfe=63.18 W</td>
<td>A) Standard efficiency type</td>
</tr>
<tr>
<td></td>
<td>B) At non-unity iron loss correction factors: Kbh=1.51, Kbr=2.234 Kbr=1.52, Kbr=1.20 Pcu=346.74 W Pfe=102.95 W Pfe=380.55 W Pfe=118.03 W Pfe=609.29 W Pfe=956.03 W</td>
<td>B) At non-unity iron loss correction factors: Kbh=1.51, Kbr=2.234 Kbr=1.52, Kbr=1.20 Pcu=383.48 W Pfe=139.06 W Pfe=10.72 W Pfe=63.18 W</td>
<td>Pfe=57.9 W Pfe=180.4 W Pfe=46.0 W Pfe=45.9 W</td>
</tr>
<tr>
<td></td>
<td>Stator iron loss, 207.2 W Rotor iron loss, 136 W Total iron loss, 343.2 W</td>
<td>Stator iron loss, 207.2 W Rotor iron loss, 136 W Total iron loss, 343.2 W</td>
<td>Tested=262 W</td>
</tr>
</tbody>
</table>

Table 1: Comparison of results.

References