Optimum Design Parameters for Synchronous Reluctance Motors

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Abstract-A series of synchronous reluctance motors (RSM) are analysed using finite element methods. The amount of iron in each rotor is kept the same. It is shown that the saliency ratio is not only dependent on the flux guide reluctance factor but also on the position or span of flux guides. It is also shown that an axially laminated design may not be an optimum configuration due to large number of flux guides. It is shown that proper distribution of magnetic and non-magnetic materials can result in improved performance.

Index Terms-Electrical Machines, Synchronous Reluctance Machines, Finite Element Method.

I. INTRODUCTION

There has been extensive research carried out in sixties and seventies to improve the performance of synchronous reluctance motors [1-7]. The earlier designs were generally provided with cage windings for starting purposes, and hence less flexibility was available in changing the electromagnetic design structures. With modern developments in power switching devices, these motors can be started and ramped to normal speed without starting cage. This has given the designers an opportunity to revisit the electromagnetic design of such motors and optimise the motor configuration. Several efforts have been made to identify practical rotor structures, which have high saliency ratios. The stator of such machines is similar to a standard polyphase AC motor with conventional winding.

Earlier applications had been rather specialized, hence performance had been of secondary importance and reluctance machines were mostly of simple salient pole construction. The earlier attempts to improve performance and optimize design of simple salient pole designs had little success due to low saliency ratio. To improve the performance, other quite different rotor configurations had emerged over the years [7-11]. These configurations result in improved overall performance but had been inferior compared to well established squirrel cage induction machines, except very recently, when reluctance machines can be compared with induction motors in performance and cost. This improvement had been possible with better analytical understanding and the employment of modern computer aided design techniques [12-15]. With improvements in the performance of rotating reluctance motors, other types of reluctance machines have emerged over the years [8-11]; though rotating RSM are the bases of investigation in this thesis. The reluctance synchronous motor with conventional rotor is simple, robust, requires simple controls but is characterized by low power factor kW/kVA ratio, low torque density, and high torque pulsations. Flux-barrier and segmented rotors improve the performance of the reluctance synchronous motor but this remains considerably lower than that of induction motors and permanent magnet synchronous motors. Consequently, the search for better brushless drives deserves to be continued with the goal of finding an electric motor configuration and corresponding controller to yield to better performance. That should continue the following: high torque density, low loss, high power factor, fast torque and speed dynamics, wide speed range control, simplicity and robustness of motion controller, and low overall costs and weights. A series of rather recent worldwide research and development efforts suggests that distributed anisotropy rotor reluctance synchronous machine and drives with advanced control are very promising candidates to meet the above mentioned demanding goals both in line-start and in variable speed drives. Many researchers extensively conducted research on line-start RSM machine during the sixties and the seventies [9-11].

The requirement of a squirrel cage for starting, along with other factors, compromised the rotor design that led to relatively poor performance compared to an induction machine. This resulted in the RSM being mainly ignored until the beginning of 1990s. However, the dramatic development of power semiconductor devices and modern control methods over the past decade has led to the emerging and availability of high performance RSM drives. The use of inverter to control the RSM machine has the effect of elimination of the starting cage from the rotor thus it can be designed to give the maximum saliency ratio \( \frac{L_d}{L_q} \). The main reasons for the renewed interests in the RSM are:

Small to medium size high performance drives may have simpler control using the RSM as compared to the field oriented controlled induction machine.

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Improved saliency ratio makes the RSM competitive with an induction machine, particularly in terms of power factor and inverter kVA requirements. It can be operated stably down to zero speed at full load unlike an induction motor, which may suffer overheating problems. In addition, RSM appears to be more efficient at low speed than an induction machine. The RSM has no magnets, which is an advantage over the permanent magnet machines in high temperature and high-speed applications. As a consequence it does not also suffer from demagnetization problems. The simple salient-pole construction is very robust and as such suitable for spindle drives.

II. PRINCIPLE OF SR MOTORS

The reluctance synchronous machine (RSM) is usually obtained by replacing the rotor of a conventional induction machine with a rotor having different inductances along its direct and quadrature axes (Ld and Lq). In its simplest salient pole form, it is similar to the classical synchronous machine without a field winding. However, unlike the synchronous machine, it can only operate at lagging power factor, since all the excitation is from the stator. The principle of operation of reluctance machines is based on existence of variable reluctance in the air gap of the machine, high reluctance in the quadrature axis (q-axis) and low reluctance in the direct axis (d-axis). The linear-start reluctance motors start as induction motors and hence, provided with squirrel cage bars, on the rotor. The stator is similar to the stator of induction counterpart. The motor is accelerated under the influence of induction motor torque and near synchronous speeds, pulled-into synchronism with the synchronously rotating stator field.

The synchronous motor would run at synchronous speed, once synchronized, irrespective of variation in supply voltage or load. Figure 1, shows the diagram of a simple reluctance motor, where the entire magnetic circuit consists of iron and air. Electrically, the stator carries one winding, but the rotor is unexcited. If the stator is excited by a current of any waveform, the rotor will in this case experience a torque except when the rotor axis is aligned with the stator axis.

It is well known fact that the operation of the reluctance motor is based on the minimum reluctance principle, that is the rotor will always try to align its poles with the position that provides minimum reluctance (corresponding to the minimum stored energy in the system). In other words, the torque in a reluctance motor is developed by virtue of a change in the reluctance with the rotor position. Based on this principle, a reluctance motor is different from any other electric machine such as synchronous or induction machine. Although there are many different reluctance machine designs, the operating principle of all these machines are the same.

III. DESIGN ASPECTS

The RS motor design can be optimised by considering the following rotor parameters as variables [10-12].

\begin{align*}
\text{Channel width} & = \text{channel arc/pole pitch} \\
\text{Flux barrier thickness (T)} & = \text{flux barrier arc/pole pitch} \\
\text{Number of flux barriers per pole (n)} & = \text{flux barrier arc/pole pitch} \\
D_c & = \text{Channel depth} \\
\gamma & = \text{Channel width/pole pitch} \\
W & = \text{Length of flux barrier} \\
T & = \text{Total flux barrier thickness} \\
d & = \text{Distance between the flux barriers} \\
n & = \text{Number of flux barrier per pole} \\
\lambda & = \text{Flux guides pitch/pole pitch} \\
t & = \text{Flux barrier width/(barrier + iron} \\
\text{lamination) thickness} \\
L_d & = \text{Direct axis inductance} \\
L_q & = \text{Quadrature axis inductance} \\
L_d/L_q & = \text{Inductance ratio}
\end{align*}
L_d - L_q = Inductance difference

Figure 2: RSM motor with two-flux guide per pole rotor configuration

IV. ANALYSIS AND DISCUSSION

A machine of a rated power of 550 W, 2-poles is analysed. The magnetic field in the machine under study is assumed to be two-dimensional. The machine is excited with the rated current. The magnetic circuits of the one-flux guided rotor (one flux barrier per pole in the rotor), two flux guided rotor, three flux guided rotor and multi-flux guided rotors have been analysed. For the sake of simplicity the effect of the flux barriers are investigated without a channel or cutout area. Also the effect of the channel has been considered for each particular optimum design.

The finite element field is plotted for the two extreme cases of d-axis and q-axis excitation. Little flux enters the rotor when the flux is forced to pass through the q-axis and more flux enters the rotor when the flux is forced to pass through the d-axis.

A. RSM with One flux Guided Rotor

The rotor of this motor has one flux per pole as shown in 3 a). In other words the rotor contains two flux barriers for a two polar design. The flux barrier’s position and its division affect the d-axis and q-axis inductances. Fig 3a) is a design with non-optimum position of flux barriers. In this configuration the L_d / L_q = 1.89 and L_d - L_q = 0.16H, because the flux barriers in q-axis, cannot provide enough reluctance to break the flux paths as illustrated in Figs 3b) and 3c).

Fig 4a is close to an optimum design of one flux-guided rotor. The flux barriers are placed at the optimum position. Therefore this configuration results in high flux in the d-axis and low flux in the q-axis. This can break most of the flux linkage through the rotor as shown in Fig 4c and minimize the L_q and airgap magnetic flux density for the q-axis. As a result, much larger L_d’ / L_q’ = 2.49 and L_d’ - L_q’=0.21H is achieved.

An other design with all the parameters in it as in Figure 4., except the existence of channel on the rotor's surface (channel depth is D_c = 3mm). The effect of channel is to reduce L_q further as in Fig 4c) but also at the cost of reducing L_d because of decreased iron area in the d-axis as shown in Fig 4.38b). The results of FEM simulation for this design shows L_d / L_q = 2.47 and L_d - L_q = 0.28H, it is obvious that the optimum, one flux guided rotor even without channel reaches high value of inductance ratio and inductance difference.

B. RSM with 2 Flux Guided Rotor

The same technique in design optimisation is used for different flux numbers. In the following paragraphs, optimum design will be demonstrated.

The rotor design with two flux barriers per pole is called the two flux guided rotor. In this design, the same amount of T per pole is maintained as in a one flux guided rotor (Figs 3 and 4). In Fig 5 both flux barriers are located at optimum locations resulting in a high flux path for the d-axis and a high reluctance in q-axis. It can be concluded that the design depicted in
Fig 5 is close to optimum for such a machine since its 
$L_d/L_q=2.85$ and $L_d - L_q =0.28H$.

Figure 5: A two flux guided RSM

C. RSM with 3 Flux Guided Rotor

The influence of flux barrier position has been 
considered in the previous designs. The following 
consideration focuses on the effect of three flux 
barriers per pole with reference to the optimum one 
and two flux guided rotors (Figs 4 and 5). The total 
flux barrier thickness per pole is kept the same as that 
shown in Fig 4 or Fig 5. A comparison between the 
optimum one and two flux guided rotor designs (Figs 
4 and 5) with three flux guided rotor design (Fig 6) 
shows that as the number (n) of flux barriers per pole 
increases, this does not necessarily result in a better 
saliency ratio ($L_d/L_q$). Therefore for this size of 
motor (550 watts) one flux guided rotor design as 
shown in Fig 4, can produce high saliency ratio than 
all other types.

D. RSM with Multi-Flux Guided Rotor

Any design with more than three flux barriers per pole 
is referred to as a multi-flux guided rotor design.. The 
following showing design is a synchronous reluctance 
motor with 5 flux guided bars (Fig. 7). The position of 
the flux guided bars is the most important parameter 
that will define the ratio $L_d/L_q$ and the difference $L_d - 
L_q$. The number of flux guided is increased to 10 and 
20 these motors are being fabricated and the results 
will be showing very soon.

Figure 7: A multi flux guided RSM (5FG/pole)

V. SIMULATION RESULTS

Many designs are analyzed. However the discussion 
will be limited here. The results of the simulation are 
shown in the table 1. It shows a comparison between 
the effective inductance that was calculated by using 
the stored energy in the motor. Effective inductance 
can be calculated as in (1). The stored energy is 
calculated using the finite element package Ansoft.

$$L_{eff} = \frac{2W}{I^2}$$

(1)

<table>
<thead>
<tr>
<th>Motor</th>
<th>$L_d$</th>
<th>$L_q$</th>
<th>$L_d-L_q$</th>
<th>$L_d/L_q$</th>
</tr>
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<tbody>
<tr>
<td>1FG Non Optimum</td>
<td>0.34</td>
<td>0.18</td>
<td>0.16</td>
<td>1.89</td>
</tr>
<tr>
<td>1FG Optimum</td>
<td>0.348</td>
<td>0.14</td>
<td>0.21</td>
<td>2.49</td>
</tr>
<tr>
<td>+Channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1FG Optimum</td>
<td>0.424</td>
<td>0.143</td>
<td>0.28</td>
<td>2.97</td>
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<tr>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2FG</td>
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<td>0.151</td>
<td>0.28</td>
<td>2.85</td>
</tr>
<tr>
<td>3FG</td>
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<td>0.115</td>
<td>0.31</td>
<td>3.65</td>
</tr>
<tr>
<td>5FG</td>
<td>0.492</td>
<td>0.12</td>
<td>0.37</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 1 : Inductance for different RSM designs.
the machine. Even a large flux barrier placed in a non-optimum position may not result in an improved design because of a reduction of both $L_d/L_q$ and $L_d-L_q$. This description can cover all different models of flux guided rotor such as, one flux guided rotor, two flux guided rotor, three flux guided rotor and multi-flux guided rotor.

VI. EXPERIMENTAL MACHINES

Figure 8 shows one of the experimental rotors, designed and fabricated to assess their performance. Figure 9 shows the experimental results of load test of 3 flux guided RSM. It is shown that the efficiency of fabricated machine is higher than the one of induction motor especially at low speed.

As mentioned earlier, the basic criteria for a good design is to have a high saliency ratio ($L_d/L_q$) accompanied by a high $(L_d-L_q)$, i.e. a high $L_d$ and low $L_q$. Finite element package is employed to compute the flux distribution and inductances. The reluctance motor is driven as a brushless variable speed drive with position sensor. The reluctance motors can also be driven as synchronous motor with inverter in open-loop control without position sensor. The other purpose of this study is to show the importance of employing multi-flux guides, even in small power machines. All the experimental machines are based on an equivalent 2-pole, induction motor of 550W rating. It can be seen that by increasing the number of flux barriers, the saliency ratio has increased. This is due to the fact that proper arrangement of insulation and magnetic material in the rotor can result in high saliency ratio and not the amount of insulation and magnetic material.

VII. CONCLUSIONS

A series of experimental reluctance machines, with solid rotor design has been proposed. These designs are of flux-guided with different flux guided number. The designs are based on an equivalent 2-pole, induction motor of 550W rating. It is shown that proper distribution of magnetic and non-magnetic materials can result in high saliency ratio and also high $(L_d-L_q)$, a pre-requisite for high performance. The performance of one such machine is given when driven as a variable speed drive.
REFERENCES


