ABSTRACT

Abstract - The electromechanical energy conversion plays an important role in the production and consumption of electrical power. For this reason, the efficiency improvements in electric motors and generators are of great importance due to the growing energy demand, the rising cost of fossil energy and greater environmental concern. In this context, there have been recent developments of reluctance machines with permanent magnets in the stator, providing high power densities, high efficiency and a robust structure, thanks to a simple homogeneous rotor.

In this thesis, it is presented an analysis of the characteristics of this type of electrical machine, with focus on the electromagnetic field phenomena. It was first considered a simplified topology for this electrical machine, studying and analyzing its advantages and also drawbacks. The electrical machine is composed by a stator with permanent magnets responsible by the excitation of the machine and a salient homogenous rotor. These magnetic and geometric features lead to the necessity of studying the magnetic circuit of the machine, namely the electromagnetic forces which cause a cogging torque that can cause mechanical stresses in its structure. More complex topologies are suggested, which would allow attenuation of the cogging torque and its effects. In short, the viability and potential of using these type of electrical machines as low or high speed generators will be analyzed.

1. OPERATING PRINCIPLE

This chapter explains the operating principle of the theoretical model on a more simplified situation. It was initially considered a simplified topology of the reluctance machines with permanent magnets shown in Figure 1, which will serve initially, to study the operating characteristics of this type of electrical machine. Figure 1 shows the machine composed by a stator with a pair of magnetic saliences and a magnetic rotor also with a pair of saliences, both made of ferromagnetic material. The excitation is created by two permanent magnets embedded in the magnetic circuit of the stator, and an electric inductor is deployed around the stator magnetic saliences.

In the energy conversion process, the excitation magnetic flux passing through the coil should vary with the angular position of the rotor as a consequence of the variation of magnetic reluctance of the magnetic circuit. This variation is achieved by varying the cross-section between the rotor section and stator section, which will change the magnetic reluctance located in the air gap for different angular positions of the rotor.

Based on the circuit described, we obtain the equation system shown in (1) for the magnetic circuit. $R_{ar}(\theta)$ Depends on the rotor’s angular position, and it is the magnetic reluctance of the air gap between the rotor and the stator. That variable has a nonlinear progress, and has to be numerically calculated.

\[
\begin{align*}
N \frac{B_{r}}{\mu_{m}} l_{m1} &= R_{ar}(\theta) \phi_{ar} + \frac{l_{m1}}{\mu_{m}} \phi_{1} \\
N \frac{B_{r}}{\mu_{m}} l_{m2} &= R_{ar}(\theta) \phi_{ar} + \frac{l_{m2}}{\mu_{m}} \phi_{2} \\
\phi_{ar} &= 2\phi_{1} = 2\phi_{2}
\end{align*}
\]

(1)

By solving the equation system, we obtain the flux, which multiplied by the number of turns of the inductor, leads to the flux linkage. Thus, considering a state of emptiness, we have in (2) the flux linkage of the system that has the progress shown in Figure 2. As expected, the flux is maximized when the rotor salience is aligned with stator salience (0 degrees).

\[
\psi = N \phi = \frac{N(Ni + \frac{B_{r}}{\mu_{m}} l_{m})}{R_{ar}(\theta) + \frac{l_{m}}{2\mu_{m}}}
\]

(2)
Using the Faraday’s law, which makes use of the flux linkage we determine the electromotive force that is inducted at the terminal of the inductance, as shown in (3).

\[ u(t) = e(t) = \frac{\partial R_{ar}(\theta)}{\partial t} \frac{N B_R}{\mu_m l_m} (R_{ar}(\theta) + \frac{l_m}{2\mu_m S_m})^2 \]

On Figure 3 we show the progress of the electromotive force, with the rotor running at the frequency of 50 Hz.

In order to find out the electromagnetic torque it is necessary, first, to determine the co-energy of the system, presented in (3). Determined the co-energy, then we get the electromagnetic torque in (4).

\[ W_{m}^{c} = \int_{l_0}^{l} \psi d i = \frac{1}{2} \left[ \frac{(Ni + \frac{B_R}{\mu_m l_m})^2}{R_{ar}(\theta) + \frac{l_m}{2\mu_m S_m}} \right] \]

(3)

\[ T_{el} = -\frac{1}{2} \frac{\partial W_{m}^{c}(\theta, i)}{\partial \theta} = \frac{N i + \frac{B_R}{\mu_m l_m}}{R_{ar}(\theta) + \frac{l_m}{2\mu_m S_m}} \]

(4)

The progress of the electromagnetic torque is shown in the Figure 4.

In this new study was intended to structurally change the machine in order to make better use of the iron proprieties. This improvement consists in reverting the magnetic flux \( \phi \), that goes through the conductor’s plane \( S \) to reversing its direction. In the model studied previously only one direction of the flow contributed to the electromotive force, that has been solved with the new structure shown in Figure 5.

Using the results obtained previously, we easily developed the electromagnetic model required to simulate the electromagnetic behavior of this new topology. To determine the influence of the magnetic dispersion on the machine, we simulated the machine using a 2D finite element program (FEMM). Were taken as reference the dimensions listed in Table 5.
Table 1 - 4/2 machine dimensions

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent magnet height</td>
<td>16 mm</td>
</tr>
<tr>
<td>Permanent magnet width</td>
<td>5.2 mm</td>
</tr>
<tr>
<td>Axial length</td>
<td>18 mm</td>
</tr>
<tr>
<td>Magnetic flux density</td>
<td>1.4 T</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>64 mm</td>
</tr>
<tr>
<td>Stator inner diameter</td>
<td>32 mm</td>
</tr>
<tr>
<td>Rotor outer diameter</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

The flux linkage and torque progress for this new topology is shown in the Figure 6 and 7.

Although the flux generated by the magnet may be slightly higher in the last simulation, due to the magnetic dispersion, which leads to a reduction of the equivalent reluctance of the magnetic circuit, the magnetic flux which passes through the inductor is much lower. As shown in Figure 9, this flux linkage reduction is caused by the magnetic saturation in rotor and stator saliences, and by the dispersive effects, leading magnetic flux out of the intended magnetic circuit.

In order to compare the obtained results with a more realistic simulation, where the dispersion and saturation are considered, in the Figure 7 and 8 is shown the flux linkage and torque progress simulated in FEMM.
3. IRON LOSSES

The Joule losses in iron are caused by both, magnetic hysteresis and Foucault currents. Those iron losses are respectively calculated using the following expressions:

\[
\begin{align*}
    p_h &= K_h f B_{\text{max}}^\alpha \\
    p_f &= K_f (B_{\text{max}} f \delta)^2
\end{align*}
\]  

(4)

Where,
\( \delta \) = Iron plates thickness;
\( B_{\text{max}} \) = Maximum magnetic field;
\( f \) = Electrical frequency;
\( K_h, K_f \) = Constants dependent on iron volume and its magnetic features;
\( \alpha \) = Estimated value (from 1.5 to 2.5)

In reluctance machines with permanent magnets in the stator, iron losses are concentrated mainly in rotor and stator saliences. The induced electric field frequency is given by the multiplication of the mechanical frequency with the number of rotor saliences (the machine in study has two rotor saliences).

\[ f = N_{\text{rotor saliences}} f_m \]

(5)

Comparing it with a standard permanent magnet synchronous machine with a pair of saliences, the hysteresis losses will be two times higher and Foucault losses four times higher, since the electrical frequency doubles.

4. SOME CONSTRUCTIVE SOLUTIONS TO REDUCE THE NEGATIVE COGGING TORQUE EFFECTS

The cogging torque that arises due to reluctance variations is an undesirable torque that causes wear and threatens the machine integrity and of what is attached to it. The decrease of the negative effects of these forces, leads to an increase of the machine lifetime and to a decrease in maintenance costs.

There are several constructive solutions that allow the cogging torque mitigation and hence its negative effects. Note that in all these solutions are associated performance costs that must be taken in consideration.

4.1. THREE-PHASE MACHINE: THREE MACHINES COUPLED

In order to mitigate the cogging torque negative effects, we decided to study a three-phase solution. The aim of this solution is to replace the machine for smaller machines that, in their total, produce the same power. Three identical machines will be coupled on the same shaft, whose stators are positioned with an offset of 120°, as illustrated in Figure 11. The rotors on the other hand have no gap between them lying directed in the same way.

In this solution, the drawbacks are related with a performance deration, and a size and weight increase.

4.1. 6/5 SALIENCES SOLUTION

Another way to increase the cogging torque frequency is to increase the number of rotor and stator saliences. In Figure 12 is shown a constructive solution where the number of stator and rotor saliences is increased.

The drawbacks of this solution are related with increased stator constructive complexity and increased Joule losses, mainly due to the Foucault currents. Foucault losses are proportional to the square of electrical frequency, this solution is thus poorly suited for solutions that require high rotation frequencies.

5. CONCLUSIONS

Were demonstrated the energy conversion in reluctance machines with permanent magnets, concluding that the cogging torque is a characteristic of this kind of machine. This
cogging torque that threatens the physical integrity of the machine, is essential for the energy conversion.

The solutions studied for the cogging torque attenuation by increasing their frequency, does not fully solve the problem, only mitigate the negative effects of this torque on its physical structure. The solution of dividing the machine by modules, leads to an increment in the size and weight resulting in more iron and copper losses. The solution of increasing number of projections, leads to a constructive complexity increase and an increase of joule losses due to eddy currents.

This type of machine is suitable for applications that require a high speed, cheap, simple and robust generator but on the other hand, does not require the machine to last enough, to the negative effects of the cogging torque to reflect on the equipment’s physical structure. Such as guided missiles.

6. References


