PLC control of an electromechanical converter with rolling rotor and axial air-gap

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Abstract – This paper presents the operation control of an electromechanical converter with rolling rotor (ECRR) and axial air-gap using a PLC. The electromechanical converter consists of a disk-type rotor made of ferromagnetic material and a stator made of twelve magnetic poles sequentially fed from a DC power source. The influence of the axial air-gap value on the speed of rotation and on the starting torque is established. The time variation of the electromagnetic torque on different switching periods is presented. Also, the influence of the magnetic poles number on the rotor speed is determined. The main advantage of this type of electromechanical converter is identified in the low rotation speed without using mechanical gearboxes.

Keywords – PLC, disk-shaped rotor, rolling rotor, low speed of rotation, axial air-gap

1. INTRODUCTION

The late exponential development of the automatic systems has led to the revival of the field of special construction electric machines by the appearance of new constructive and functional solutions. The special construction electric machines operates on the same principles of electromechanical energy conversion as the conventional electric machines, but differ from these latter by the steady and dynamic state characteristics and not least through construction.

The electromechanical converters with disk-shape rotor and axial air-gap have been developed quite most often due to the rotor low inertia [3]. In order to establish the usage possibilities of an electromechanical converter, most often, its power and speed are indicated. The designation of these parameters is not always sufficient for the assessment of their behavior in load conditions. There are various types of electromechanical converters for which the angular displacement is reduced and the expression of power has no significance [3]. In general, for knowing the operating conditions of an electromechanical converter is indicated to establish the useful torque that it can develop in different revolution regimes.

The electromechanical converter with rolling rotor and axial air-gap (ECRR) analyzed in this paper shows a rather slow speed, sometimes invisible to the unaided eye, which can grow to a revolution per day or less, without the use of mechanical gearboxes. The reduced speed is achieved due to the use of a disk-shaped rotor that rolls on a flat surface, under the influence of the rotating magnetic field obtained through the successive activation of the magnetic poles in the stator structure. Thus, the ECRR speed depends on the switching period of the stator poles and axial air-gap size.

In the paper the experimental results related to the variation of rotational speed with on-load and no-load operation are presented. There are shown the initial torque with locked rotor variation for different switching periods of stator poles and the useful torque variation in load conditions. The modification of the ECRR operating parameters in order to obtain the operating characteristics was made possible by using a PLC, through which has been changed the switching period of the stator poles and their number.

2. THE ECRR CONSTRUCTION AND OPERATING ASPECTS

From a constructional point of view, the ECRR prototype is characterized by simplicity due to the lack of the windings in the rotor. The stator is made up of twelve equally spaced magnetic poles placed on a flat surface on a circular path. The rotor is massive, made of ferromagnetic material and is rolling on a flat surface being under the influence of the stator rotating magnetic field. The rotation movement of the rotor is transmitted to the rotor axis through a special joint that enables the modification of the rotor position without existing the axis inclination.

The ECRR operation is based on the existence of friction between the stator and rotor. Thus, both on the rolling surface and on the bottom surface of the rotor, two silicone rubber rings were fixed in order to obtain a larger friction coefficient and to eliminate the slippage between the rotor and the stator. If slipping is neglected...
it can be said that for a certain load variation domain, the ECRR operates in the synchronism. A three-
dimensional image of the ECRR experimental model is shown in Fig. 1.

Actually, the ECRR operation is based on the difference between the radius of the rotor and the radius of its rolling path. When successive magnetic poles are activated, a rotating magnetic field appears and the rotor is under the influence of magnetic attraction forces. An explanation concerning the ECRR operation is presented in Fig. 2.

For a full activation cycle of the stator poles with the angular velocity $\Omega_T$, the contact mobile point rotates with an angle equal to $2\pi$. Thus, the rotor will perform a much lower angular displacement $\Omega_r$, in the sense of the stator poles commutation. As shown in Fig. 2, the contact point A moves on a circular path due to the tangential force that acts on the rotor and on the friction force between stator and rotor. The maximum value of the tangential force depends on the friction coefficient $\mu$ and on the magnetic force of attraction $F_e$, according to the relation:

$$F_{tg\text{max.}} = \mu F_e$$ (1)

The ECRR rotation speed is dependent on the mechanical gear ratio according to relation [2]:

$$\Omega_r = \frac{\Omega_T}{i}$$ (2)

Assuming that the axial air-gap is constant and the slipping between the stator and rotor can be neglected, the mechanical gear ratio can be defined by relation [2]:

$$i = \frac{R_r}{R_s}$$ (3)

where $R_r$ and $R_s$ is the rotor radius and the rolling path radius.

According to relations (2) and (3), the rotor will perform a much lower rotating speed compared to the contact point A speed, in a gear ratio which is dependent on the value of the axial air-gap and on the difference between the two radii, $R_r$ and $R_s$ respectively.

Therefore, a magnetic attraction force is needed so as for the contact point A to move continuously on the periphery of the stator, on the rolling path.

3. EXPERIMENTAL TEST BENCH

For the ECRR operating study, an experimental test bench was built in order to find out the rotational speed, the mechanical power and the starting torque. For the ECRR operation control, it was accomplished a command module consisting of an XC-CPU101-C256K programmable automaton and an XC-12DO-R auxiliary module, necessary for the sequential activation of the stator poles.

In general, for low power electromechanical converters, the torque measurement is a very complicated issue due to its unstable nature. Thus, as it will be show in this paper, the torque developed by the ECRR is not constant but on the contrary it presents variations in time close to the average value due to the stator poles sequential switching and to the magnetic circuit reluctance modification. At low rotational speed, the torque ripple are consistent and lead to an load oscillatory operation and to a non-uniform rotation speed. In these conditions, we can speak of a torque ripple coefficient determined by the relationship:

$$\gamma = \frac{M_{\text{max}} - M_{\text{min}}}{M_{\text{max}} + M_{\text{min}}} \times 100$$ (4)

Therefore, the switching at the level of the stator circuit limits the operation of ECRR.

In order to determine the initial starting torque value (with locked rotor), a IMADA HTG2N digital measuring device was used with a 0,001 Nm resolution and it can measure up to 2Nm. The measured values can be displayed and stored through a graphical interface. The experimental test bench for the analysis of ECRR, in dynamic regime, is shown in Fig. 3. In order to determine the torque of the ECRR in dynamic conditions within the limits in which the operation is stable, it was firstly determined the power output through the string brake method, that does not require speed measuring. Thus, on the disc fixed to the shaft end, a durable thread was attached, that has at its other end a weight, G. Following the stator circuit powering, the G weight will be lifted in a time, $t$, on a certain distance, $h$. The power output of the ECRR is determined by the relationship:
where, g is gravitational acceleration [m/s²], G is the attached weight [g], h is the height at which the weight is lifted [cm], t is the time required for the weight lifting [s].

\[ P_2 = g \frac{Gh}{t} \times 10^{-5} [W] \]  
(5)

Knowing the power output and the rotor angular velocity, the useful torque can be found out, with the relationship:

\[ M_2 = P_2 / \Omega_r \]  
(6)

The angular velocity \( \Omega_r \) was measured with a 1/1000N CarlZeiss incremental encoder and monitored through a graphical user interface achieved in the XSoft CoDeSys program. An image with graphical interface that ensures the ECRR control operation by changing the switching period of the stator poles is presented in Fig. 4. Through the graphical interface, the angular velocity can be determined in RPM or radian per seconds, based on the impulses provided by the incremental encoder.

4. TEST RESULTS

In a first stage, the angular velocity \( \Omega_r \) on no-load and on-load operation was measured. In order to highlight the influence of the stator poles switching period on the \( \Omega_r \) angular velocity and then on the torque, the following values were set: 25ms, 50ms, 100ms, 250ms and 500ms.

Another parameter that affects the \( \Omega_r \) angular velocity and the torque is the axial air-gap. That is why, the experimental study took also into account the variation of this parameter.

The electrical and geometrical parameters of the ECRR prototype are shown in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA supply voltage [V]</td>
<td>12</td>
<td>( U_n )</td>
</tr>
<tr>
<td>Consumption power [W]</td>
<td>12</td>
<td>( P_n )</td>
</tr>
<tr>
<td>Winding inductance [H]</td>
<td>64x10⁻³</td>
<td>( L )</td>
</tr>
<tr>
<td>Number of turns on each pole</td>
<td>1090</td>
<td>( N )</td>
</tr>
<tr>
<td>Ampere turns [At]</td>
<td>817.5</td>
<td>NI</td>
</tr>
<tr>
<td>Number of stator poles</td>
<td>12</td>
<td>( 2p )</td>
</tr>
<tr>
<td>Wire diameter [m]</td>
<td>0.45x10⁻³</td>
<td>( d )</td>
</tr>
<tr>
<td>Rotor diameter [m]</td>
<td>0.310</td>
<td>( D_r )</td>
</tr>
<tr>
<td>Rotor thickness [m]</td>
<td>0.003</td>
<td>( t_g )</td>
</tr>
<tr>
<td>Stator diameter [m]</td>
<td>0.340</td>
<td>( D_s )</td>
</tr>
<tr>
<td>The height of ECRR [mm]</td>
<td>0.200</td>
<td>( H_{ec} )</td>
</tr>
<tr>
<td>The main dimensions of the EA</td>
<td>60x25x40</td>
<td>Lxwxh</td>
</tr>
</tbody>
</table>

It has to be mentioned that, as the switching frequency increases, a decrease of current through the powered winding takes place, thus leading to the diminishing of the attraction force between rotor and stator. At the same time, the increase in size of the axial air-gap has the same effect on the attraction force. Fig. 5 shows the variation of current through the winding of a stator pole, depending on the switching period of the stator poles.

![Fig. 5 Current variation as function of the stator poles switching period](image)

Fig. 5 shows the \( \Omega_r \) angular velocity variation, depending on the stator poles switching period at a value of 2 mm of the axial air-gap, while Fig. 7 shows the same curves but at a different value of the axial air-gap (\( d=4.5mm \)). Analyzing Fig. 6 and Fig. 7 an increase of the angular velocity can be observed with the...
decrease of the number of successively activated stator poles, considering a constant value for the axial air-gap. The increase of the axial air-gap value leads to higher angular \( \Omega \) velocity values, only for two of the four considered cases (Fig. 7). If we admit for the stator circuit \( 2p=4 \) and \( 2p=3 \), the ECRR operation is not stable, the angular velocity having uneven growth trends. Therefore, for \( T=25\text{ms} \), \( 2p=12 \) and \( 2p=6 \) respectively, the angular velocity \( \Omega=0 \). Also, for \( T=50\text{ms} \) and \( 2p=6 \), the angular velocity \( \Omega=0 \).

Due to the axial air-gap value variation, the magnetic reluctance is not constant. This fact has a negative influence on the ECRR torque. Because of the concentrated windings, equidistantly disposed on the surface of the stator, the force is not applied continuously on the rotor, resulting variations in the produced torque as in rolling rotor switched reluctance motors [1], [3], [4], [6].

The electromagnetic torque variation over time, with locked rotor, at the stator poles switching period of \( T=50\text{ms} \) and axial air-gap of \( d=2\text{mm} \), is presented in Fig. 8. The variations of the starting torque for \( T=25\text{ms} \) and \( T=500\text{ms} \) are presented in Fig. 9 and Fig. 10. For the other switching periods (100ms and 250ms) the time variation of the starting torque with locked rotor has the same shape.

Also, the variation of the maximum starting torque with locked rotor, for the five steps of the switching period is shown in Fig. 11. An obvious increase of the starting torque can be observed, only for stator poles switching periods from the interval 25ms - 100ms, after which the growth trend is insignificant. The maximum value of the starting torque is about 1,106 Nm and it was obtained for \( T=500\text{ms} \).

Another part of the experimental study refers to the determination of the ECRR mechanical power. Thus, through the brake method described above, the ECRR mechanical power was determined. Seven levels of weight were taken into account, starting from 500 g up to 3500 g. It should be noted that over the 3500g value, the ECRR resistant torque exceeds the maximum useful torque and the angular velocity becomes null.
Fig. 11 The variation of the maximum starting torque as function of the switching period, for 2 mm axial air-gap value and 2p=12

Fig. 12 shows the rotor speed variation as function of the mechanical power, considering an axial air-gap value equal to $d = 2\, \text{mm}$. For the two switching periods of the stator poles: $T=500\, \text{ms}$ and $T=250\, \text{ms}$, an increase of the mechanical power can be observed, simultaneous to the rotor speed decrease.

Fig. 12 The rotor speed variation as function of the mechanical power, for $T=500\, \text{ms}$ and $T=250\, \text{ms}$.

The $n=f(P)$ curves for switching periods of $T=100\, \text{ms}$, $T=50\, \text{ms}$ and $T=25\, \text{ms}$ are presented in Fig. 13.

Fig. 13 The rotor speed variation as function of the mechanical power, for $T=100\, \text{ms}$, $T=50\, \text{ms}$ and $T=25\, \text{ms}$.

CONCLUSIONS

This paper presents an experimental analysis of ECRR in order to assess the possibilities of use in different fields.

The ECRR prototype is characterized by low angular speed without using mechanical gearboxes. The ECRR shows a simple construction, the rotor is massive, disk-shaped, without windings. The angular speed control can be achieved by changing the size of the axial air-gap or the switching period of the stator poles. For powering up the experimental model, a PLC and an auxiliary module for controlling each magnetic pole were used.

On the ECRR no-load operation, it was observed that with increase of the switching period, the angular speed also increases. Reducing the number of stator poles lead to an increase of the angular speed. Any increase in the size of the axial air-gap results in the increase of the angular speed but shows negative effects on the mechanical power and useful torque developed by the ECRR prototype.

The starting torque with locked rotor at constant value of the axial air-gap increases with the stator poles switching period decrease. Instead, the ECRR useful torque increases as the angular speed decreases at constant switching period. It can also be noted that the decrease of the angular speed is more pronounced on the lower switching period of the stator poles.

The feature that is most used in the assessing of an electromechanical converter operation is the $M_2=f(\Omega)$ mechanical characteristic, which expresses the useful torque variation depending on the angular velocity. By modifying the stator poles switching period the useful torque $M_2$ and the angular velocity $\Omega$ have been experimentally determined.

The torque-speed curves $M_2=f(\Omega)$ are presented in Fig. 14, that highlight the increase of the useful torque with the decrease of the angular velocity, which is more pronounced as stator poles switching periods decrease.

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The mechanical power is significant at higher switching periods of the stator poles with consequences in rotor angular velocity decrease.

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