Three-Phase Induction Motor with Spiral Sheet Rotor

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Abstract—Improvements on the torque with low currents using rotor with spiral sheets are analyzed. Several rotors and stators have been built combining different constructive and mechanical characteristics of the related elements: inertias, constructive materials, geometrical shapes of the sheets and geometrical disposition of the sheets. These different types of motors have been simulated using computer aided tools and then tested in the laboratory. Finally, four stators (1000, 1500, 1500-type A, and 3000 rpm) having the same constructive parameters, have been simulated and tested with the following rotors types: solid rotor, solid rotor with diamagnetic rings, drag cup, and simple and double squirrel cage rotor; these results have been compared to those obtained with the seven variants of spiral sheet rotor presented in this paper.

Index Terms—Electric machines, Special machine, Spiral sheet rotor, Three-Phase asynchronous motor.

Technical Tracks—T2: Electrical machines and drives.

I. INTRODUCTION

The rotors of conventional asynchronous motors are formed by magnetic sheets packed above the shaft of the machine. The rotating magnetic field created by the stator, induces currents parallel to the shaft and so upright to the rotor sheets [1]. Those currents cannot flow between the sheets if they are electrically isolated, being necessary the intervention of conventional squirrel cage rings to close the electric circuit and thus the rotor currents can circulate.

In table I the basic mechanical characteristics of some rotors tested are presented [3]. These rotors have the same dimensions and they are assembled to stators of 1000 rpm, 1500 rpm and 3000 rpm, having the latter the same constructive parameters.

TABLE I
MAIN MECHANICAL CHARACTERISTICS OF ROTORS

Rotor types	Mass (kg)	Inertia (kg·m ²)	Kinetic energy at 1500 rpm (J)	Rotor dimensions (mm)
Squirrel cage	3.440	$2.717 \cdot 10^{-3}$	33.519	79.5 x 71
Solid rotor	3.620	$2.860 \cdot 10^{-3}$	35.283	79.5 x 71
Solid with ring	3.580	$2.828 \cdot 10^{-3}$	34.889	79.5 x 71
Diamagnetic hollow rotor	0.620	$4.898 \cdot 10^{-4}$	6.0426	79.5 x 71
Winding rotor	3.120	$2.465 \cdot 10^{-3}$	30.411	79.5 x 71
Spiral sheet, A	3.160	$2.496 \cdot 10^{-3}$	30.793	79.5 x 71
Spiral sheet, B	3.236	$2.556 \cdot 10^{-3}$	31.533	79.5 x 71
Spiral sheet, D	3.040	$2.401 \cdot 10^{-3}$	29.621	79.5 x 71
Spiral sheet, Z	3.230	$2.625 \cdot 10^{-3}$	32.384	79.5 x 71

II. MOTOR WITH SPIRAL SHEET ROTOR

Forming a rotor with spiral shape sheets [8], distributed in a radial disposition around the shaft, it is possible to generate a magnetic field in the rotor periphery, inducing peripheral emf, and currents along the same sheets, that are only active in their periphery.

The peripheral currents of this rotor have more section to circulate, compared to a normal cage rotor current.

Fig. 1. Rotors: with double cage A. Spiral sheet rotors B and C types.

Figure 4 shows a plain representation of the disposition of the sheets [9]. There are two zones: one with active currents going

through and the other is used to receive the possible returning currents (A returning currents proposal).

Fig. 2. Section of a "three-phase asynchronous torque-motor".

III. ANALYSIS OF CONDUCTIVITY

This section analyzes the distribution of currents vs. the flux density of foil motors with different electric conductivity (3, 12 and 60 MS/m each one). The induction distribution and also the current density in the foils for 5 Hz rotor frequency are analyzed [7].

Figure 10 shows that increasing conductivity of the material, the current distribution becomes more superficial. From the analysis we can bear out the existence of a field created by the rotor as the conductivity of the material increases. According to the simulations, the net field in the motor is weaker as the rotor produces a bigger field. This phenomenon is only possible if there is a bigger phase between the two fields (stator and rotor). This space phase means a change in the resistance and reactance properties in the rotor just as it is foreseeable.

A bigger conductivity obviously implies a more inductive loading that generates a reactive power. The optimization in the selection of materials relapses in the evaluation of the product of the primary current by the factor of motor power with the useful couple that it can develop. This conclusion is very important because it is applicable to any part of the motor for deciding the application of the best materials.

Supposing the reactance variation in the rotor very small, since its frequency is weak, it is possible to approach the variation of the angle of temporary phase out between the rotor current and the electromotive force as:

$$\theta = \arctg (K \cdot \sigma) \quad (1)$$

Where σ is the conductivity. Now, the width variation of B_{rotor} in relation to the I_{rotor} variation gives:

$$\partial B \propto \partial I \quad \text{and} \quad I = \frac{\vec{E}}{R_{rotor} + j \cdot X_{rotor}} \quad (2)$$

Fig. 3. Flux and current densities simulations for different conductivity values. Motor with spiral sheet rotor type A.

With their corresponding module :

$$|\vec{I}| = \frac{1}{R_{rotor}^2 + X_{rotor}^2} \cdot |\vec{E} \cdot (R_{rotor} - j \cdot X_{rotor})| = \frac{E}{\sqrt{R_{rotor}^2 + X_{rotor}^2}} \quad (3)$$

Finally, making a series development:

$$|I| \propto \frac{1}{X_{rotor}} - \frac{1}{2 \cdot X_{rotor}^3} \cdot R_{rotor}^2 \quad (4)$$

Graphically the dependence of the current module with the conductivity, for very small R_{rotor} gives:

$$|I| = K_1 - \frac{K_2}{\sigma^2} \quad (5)$$

Fig. 4. Current-conductivity in a motor with spiral sheet rotor.

The obstacles of air that finds the rotor flow facilitate the creation of a characteristic reluctance of the motor. This phenomenon facilitates in transitory a very quick answer. The high reluctance also comes accompanied by a low inertia that also supposes a low mechanical and electric time constant.

IV. CURRENT DENSITY DISTRIBUTION

Trough FEMM simulations the distribution of current density in the rotor [6] can be determined. The real component of this current density is represented in grey (figure 13).

Fig. 5. Current density distribution.

It is important to remark the evolution of current density with the radius, which is represented by sine wave function as it was expected. This current density versus the rotor radius follows a hyperbolic distribution, in particular, follows a hyperbolic tangent. The values of some electric magnitudes can also be observed in these graphs. For example, the value of the maximum current density in the rotor is approximately 1.6 A/mm^2 .

Fig. 6. Current density distribution a) sheet 1, b) sheet 2, c) sheet 3.

V. THERMAL VALUES

Thermal experiments demonstrate that the motors present different characteristics with respect to conventional squirrel cage motor, since the current, that is the main cause of the increase of the temperature in the stator winds, practically does not change when changing the load [8].

This makes these motors able to work in regimes with high slip without changing their thermal conditions. This fact is almost impossible in squirrel cage motors.

On the other hand, the spiral sheet motors are more resistive than squirrel cage motors and we can appreciate an increase of temperature with respect to squirrel cage rotors when they are working in the same conditions, but it is in any case much smaller than the increase than undergoes other rotors like the solid rotor.

Fig. 7. Thermal test of motor with spiral sheet rotor at 3000 rpm: evolution of rotor-stator temperature.

VI. MECHANICAL INERTIAS AND LOSSES

The study of mechanical losses due to the bearings, fan and air friction has been made, getting reasonable values compared to the rest of conventional motors [1]. The inertias are very similar to squirrel cage motor values; and in the worst case a light inertia increase in the spiral sheet motor are detected, which have not the rotor machined.

Fig. 8. Torque (red) and speed (blue) in a start-stop cycle of a motor with squirrel cage rotor.

Finally, the experiments done to test mechanical resistance in long term operation were satisfactory because, although these rotors have not been thought for periods with prolonged operations, they have not undergone any type of deformation.

Fig. 9. Torque (red) and speed (blue) in a start-stop cycle of a motor with spiral sheet rotor type A.

VII. PARASITIC CURRENTS

Using simulation and test of normal section it is possible to know the induction in rotor (figures 10 and 11).

Fig. 10. Magnetic simulation with FEMM. Line "a" represents the section of simulation.

Fig. 11. Magnetic induction. Sheet rotor at 3000 rpm, $c=3$ MS/m, $\mu=4000$ H/m, and $f=3.33$ Hz.

With this distribution, the e.m.f. results:

$$E = -\frac{\partial \phi}{\partial t} = -\frac{\partial B}{\partial t} S = -S \cdot B \cdot \omega_s \cdot \cos \omega_s t \quad (6)$$

Where S is the magnetic circuit area, a constant in this case.

Fig. 12. EMF distribution (distance from stator axis).

The current induced by this EMF in sheets can be calculated using the respective electric circuits, remembering that current flow inside the sheets.

Fig. 13. Vertical coordinate defining the current sense change.

This distribution is due to the EMF in the upper area of the sheets inducing a higher current in this section. The maximum current can be calculated (r is the height of the sheets from the rotor axis center):

$$|\bar{E}_1| = \int_{R_{axis}}^h \frac{k}{(A-r)} dr = k \cdot \ln \frac{A - R_{axis}}{A - h} \quad (7)$$

$$|\bar{E}_2| = \int_h^{R_{stator}} \frac{k}{(A-r)} dr = k \cdot \ln \frac{A - h}{A - R_{stator}} \quad (8)$$

$$R_{sheet} = (R_1 + R_2) = \rho_{sheet} \frac{L_{rotor}}{e_{sheet}} \left(\frac{(R_{stator} - s)}{h \cdot (R_{stator} - h - s)} \right) \quad (9)$$

$$(E_1 - E_2) = I(R_1 + R_2) = k \cdot \ln \left[\frac{(A - h)^2}{(A - R_{axis}) \cdot (A - R_{stator})} \right] \quad (10)$$

$$I = \frac{k \cdot \ln \left[\frac{(A - h)^2}{(A - R_{axis}) \cdot (A - R_{stator})} \right]}{\frac{\rho_{sheet} \cdot L_{rotor}}{e_{sheet}} \left(\frac{(R_{stator} - s)}{h \cdot (R_{stator} - h - s)} \right)} \quad (11)$$

Where the constants A , K , y and k , are values that adjust the electromagnetic field equation; s is a parameter that depends upon the current circulating through the upper sheet area. Also, h is the sheet radius; e_{axis} the sheet thickness (mm); σ is the sheet conductivity ($S \cdot m/mm^2$) and L_{rotor} is the rotor length.

As the induction is a function of the radial position of considered section, which is known; it is possible to calculate the constants A and K :

$$B_{max} = \frac{K}{(A - R_{stator})}; A = \frac{B_{min} \cdot R_{rotor} - R_{stator} \cdot B_{max}}{B_{min} - B_{max}} \quad (12)$$

$$B_{min} = \frac{K}{(A - R_{rotor})}; K = B_{min} \cdot (A - R_{rotor}) \quad (13)$$

And k is a constant function of maximum emf:

$$E = \frac{k}{(A - r)}; k = E_{max-2} (A - R_{stator}) \quad (14)$$

$$E_{max-2} = E_{max-1} \cdot \left(\frac{m_1}{m_2} \right) \cdot \left(\frac{Z_2 \cdot \xi_2}{Z_1 \cdot \xi_1} \right) \quad (15)$$

Where:

- m_1 and m_2 = number of phases of stator and rotor.
- Z_1 and Z_2 = number of turns and sheets of stator and rotor.
- ξ_1 and ξ_2 = distribution factors for stator and rotor.

All the terms are known except the radial coordinate h which corresponds to change of sense in current along the shape profile.

Fig. 14. Distribution of the active current along the radial sheet of the rotor.

With the coordinate h known, it is possible to calculate the total sheet current, by integration of the current equation between the upper and lower limits of the sheet:

$$I_{upper} = \int_h^{R_{stator}} \left[\left(\frac{k \cdot e_{sheet}}{\rho_{sheet} \cdot L_{rotor}} \right) \cdot \ln \left[\frac{(A-h)^2}{(A-R_{axis}) \cdot (A-R_{stator})} \right] \cdot \left[\frac{h(R_{stator}-h-s)}{(R_{stator}-s)} \right] \right] \cdot dh \quad (16)$$

$$I_{lower} = \int_{R_{rotor}}^h \left[\left(\frac{k \cdot e_{sheet}}{\rho_{sheet} \cdot L_{rotor}} \right) \cdot \ln \left[\frac{(A-h)^2}{(A-R_{axis}) \cdot (A-R_{stator})} \right] \cdot \left[\frac{h(R_{stator}-h-s)}{(R_{stator}-s)} \right] \right] \cdot dh \quad (17)$$

The ring per-sheet current and the total currents are:

$$I_{ring-per-sheet} = I_{upper} - I_{lower} \quad (18)$$

$$I_{total-ring} = \frac{I_{ring-per-sheet}}{2p} \cdot \frac{n_{rotor-sheets}}{\pi} \quad (19)$$

The torque is related to this total current:

$$\tau = \int_{R_{rotor}}^{R_{stator}} L_{rotor} \cdot B(r) \cdot I(r) \cdot dh = \int_{R_{rotor}}^{R_{stator}} \left[\left(\frac{K}{(A-h)} \right) \cdot \left(\frac{k \cdot e_{sheet}}{\rho_{sheet} \cdot L_{rotor}} \right) \cdot \ln \left[\frac{(A-h)^2}{(A-R_{axis}) \cdot (A-R_{stator})} \right] \cdot \left(\frac{h(R_{stator}-h-s)}{(R_{stator}-s)} \right) \right] \cdot dh \quad (20)$$

VIII. CONCLUSION

With a proper choice of the materials and constructive shapes, it is possible to obtain low starting current of induction motors. This will not suppose a decrease in their torque values, and at the same time, their life is extended considerably and the maintenance is reduced.

These motors present a high starting torque related to short-circuit current. This characteristic makes them adequate for drives in which we were asked to have a high number of starting and stops per hour. Its main inconvenience is the high cost of the tools used in the configuration of the rotor sheets, so that they should be fabricate in mass production. Nowadays there are many electrical drives of the mentioned characteristics, with increased demands.

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REFERENCES

- [1] Xiaodong Li, Qing Wu, Subhasis Nandi "Performance Analysis of a Three-Phase Induction Machine With Inclined Static Eccentricity" *IEEE Transactions on Industry Applications*, vol. 43, no. 2, march/april 2007.
- [2] D. Gonen, "Analysis of a 2-Phase Drag-Cup Induction machine" *IEEE Transactions On Power Apparatus And Systems*, Vol. Pas-85 No. 1, January, 1996.
- [3] J.F. Lindsay T.H. Barton. "Parameter Identification For Squirrel Cage Induction Machines" *Transactions On Power Apparatus And Systems*, Vol. Pas-85 No. 1, January, 1996.
- [4] Mujal, Ramón. Humet, Luis "Asynchronous Motor with spiral sheet rotor" *ICEM-2000*. p. 477-482, 28-30 August. Helsinki-Finland, 2000.
- [5] Mujal, Ramon. "Asynchronous motor with spiral sheet rotor. Improvement of the functional characteristics of the asynchronous motors" *ICEMS-2001*. p. 80-84, August 18-20. Shenyang-China, 2001.
- [6] Mujal, Ramon. "Three-phase asynchronous motor with spiral sheet rotor. Performance improvement of the three-phase induction motors". *ISC-2002*. 26-28 August. Tsukuba (Japan).
- [7] Mujal, Ramon. "Three-phase Asynchronous motor with spiral sheet rotor. Material effects and analysis". *IEEE International Electrical Machines and Drives Control*. p. 1688-1694, 1-4/3 Madison-EEUU, 2003.
- [8] Mujal, Ramón. "Electromagnetic of the induction motor with spiral sheet rotor". *EPE'05*, 12-15/9 Dresden-Germany, 2005.
- [9] Mujal, Ramón. "Analysis of the induction motor with spiral sheet rotor". *ICEM'06*, 04-06/9 Crete-Greek, 2006.