DESIGN AND FEM SIMULATION OF A FRACTIONAL POWER THREE-PHASE INDUCTION MOTOR FOR OIL-SUBMERGED APPLICATIONS

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KEYWORDS
Fractional Power Induction Motor, Design, FEM Simulation, Skewed Rotor Bars.

ABSTRACT

The paper reports design and FEM simulation comments on a fractional power three-phase induction motor with severe constraints as regards frame size and supply electric parameters. The simulation stage consists in magnetodynamic and transient analyses both in 2D and multilayer approach. The study takes into consideration different topologies (straight or skewed rotor slots, open or closed rotor slots) and two types of laminated silicon steels (with regular and premium magnetization curve) and put in view advantages and drawbacks upon motor performance.

INTRODUCTION

Nowadays, the electric drives have a wide range of solutions as regards the electric motor. The most popular refers to ac machines (induction or PM synchronous motors) or electronically commutated motors (brushless dc and switched reluctance). To choose the most profitable solution represents a challenge by itself. The constraints imposed and appreciated by the users refers not necessarily always to performance but often to purchase or maintenance or usage costs, which sometimes are connected to performance. Practically it is impossible to proclaim a certain type of machine as the right solution for an electric drive. As consequence, studies concerning the advantages and drawbacks that come out of using one or other solution are worth and much more are mandatory in evaluation of a final answer. The new concept that asks motors to be matched to their specific applications moves this responsibility back to the design and simulation stages. The design process needs to be changed and often, the regular constraints must be infringed to give place to the other ones imposed by the application. It is the case of the analysis presented in this paper. Starting with particular and unusual design data, a few comments upon the design decisions and a highly complete FEM-based simulation is presented. The results should convince the customer of the opportunity of the demanded solution.

DESIGN TASKS

The discussion about the electric machine must start with the nature of application. The electric motor is a part of a rather complicated installation and it has to operate submerged in an oil-tank. It acts as a pump (a fan wheel is placed on one extremity of the shaft) and the oil flows through the electric motor. The first and mandatory request imposed by the user refers to the motor type – a three-phase induction one. The supply system consists in a 6 V battery followed by a three-phase inverter, which requires a limitation of the line current to a 32 A value. There are also restrictions as regards frame size and the mechanical parameters (torque and speed). Table 1 presents synthetically the initial requests of the customer.

Table 1: Initial Design Data

Motor type	3 phase ind. motor
Frame size-D_{out} x L [mm]	70 x 80
Max. line current [A]	32
Rated torque [N·m]	0.19
Breakdown torque [N·m]	0.41
Speed [r/min]	5000
Output power [W]	90
Input voltage [V]	4.6

It has to be noticed that the ac supply voltage becomes 4.6 V and the torque-speed product gives an output power of 90 W.

From the very beginning some remarks has to be made. First of all, it is a fractional power three-phase induction motor which operates at high speed. Any specialist in electrical machines knows that a rotating machine with such a small power has reduced values of efficiency and power factor. This is a true challenge if we combine it with the frame size and the supply electric parameters. At a first glance, the possibility of obtaining the required torque is questionable. Any design process of

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an electric motor has as primary objectives the establishing of length, L and inner stator/outer rotor diameter, D. As a matter of fact, the electromagnetic power is proportional to the product $D^2 \cdot L$. In our case, the two geometrical dimensions are imposed by the application restrictions. As consequence, the major free design parameters remain the specific current load, A [A/m] and the air-gap flux density, B_δ [T]. Both of them determine the load degree of the active materials and an overloading is to be expected. To summarize the design features, which are not the main topic of the paper, some of the adopted solutions are presented as follows.

1. Stator winding and number of poles. The major challenge is to match the high output torque with the rotor speed. It is known that a higher number of poles lead to an intensification of the developed torque. On the other hand, the 5000 r/min rotor speed is far away to the natural synchronous speed values. Consequently, the supply frequency has to be increased. In conclusion, taking into account the stator diameter, a maximum of 6 poles is expected to be achieved. In this case, a frequency of 250 Hz is necessary to get the rotor speed close to requested value. The number of stator slots, Z_s, could be minimum 18 slots (more than 18 is not a solution from the point of view of the teeth width). It has to be accepted that this solution is of poor quality since the three-phase winding has just one slot per pole and per phase. Parasitic torques are to be expected and consequently, an alternating solution to reduce them is necessary.

2. Rotor slot number. Of great importance in operation quality of an induction motor is the correlation between the number of stator and rotor slots. The specific literature (Boldea and Nasar 2002; Pyrhonen et al. 2008) indicates the right combination in accordance with the number of poles. Unfortunately, for the fractional power machines, there is a lack of information. Obviously, the general expressions give the avoidable combinations:

$$Z_s - Z_r \neq \pm 1;\ \pm 2;\ \pm p;\ \pm(p+1);\ \pm(p+2) \qquad (1)$$

In our case, the small rotor diameter is a supplementary impediment. Finally, as a compromise solution, the number of rotor slots is $Z_r = 14$.

3. Cage winding and rotor slots shape.

a) Cage material. The rotor winding is usually made of Aluminum or Copper in extruded or die-cast technology. The Aluminum is cheaper, lighter and easier to be processed. But, its most important drawback is its higher resistivity. On the contrary, the Copper is pricey and more difficult to be used as extruded bars (brazing to end-rings is complicate) or die-cast form (expensive technology due to high melting point). Moreover, they say that under certain power values – 250 Hp according to (Malinowski et al. 2004) – the Copper cages are not profitable. However, the Copper brings a higher efficiency with 1.5-3 % and maybe more for small motors (Manoharan et al. 2009; Peters et al. 2005); a lower rated slip, a higher breakdown torque and reduced stray-load losses. Since our major fight is against a low efficiency, the Copper cage appears as the mandatory solution.

b) Rotor slots shape. Due to the constructional restrictions applied on stator winding, a skewed rotor winding is mandatory. Besides an improvement of the air-gap flux density high order harmonics, a decrease of the stator iron losses and a reduction of the current ripple in rotor bars are obtained (Kawase et al. 2009). The skew degree is also important and has a determinable effect mainly on current ripple. Usually, the skew angle of the rotor corresponds to a slot pitch of the stator but a range of (2/3÷4/3) is also acceptable. More important in this configuration is the necessity of insulating the rotor bars against magnetic circuit. In this way, the interbar currents are canceled. Otherwise, the skew technique could become even more disadvantageous than straight bar configuration.

A special attention must be paid to the shape of the rotor slots. The use of the Copper and the operation at 5000 r/min require round slots (Caprio et al. 2005; Rodrigues et al. 2008). The problem in question is whether open or closed slots should be used. The subsequent FEM-based analysis is responsible for the right solution.

4. Active magnetic material. It is desirable the use of a magnetic material with superior qualities, Vacoflux 50 for example. But for economical reasons, a regular material, Vacoflux 17 for example, is acceptable (Gieras 2008). Table 2 and Figure 1 present the main data of the resulted motor while Figure 2 gives a general 3D view of the stator and rotor magnetic circuit.

Table 2: Final Design Data

Output power [W]	90
Line voltage [V]	4.6
Supply frequency [Hz]	250
Line current [A]	30
Number of poles	6
Outer stator diameter [mm]	68
Axial length [mm]	70
Number of slots Z_s/Z_r	18/14
Air-gap width [mm]	0.2

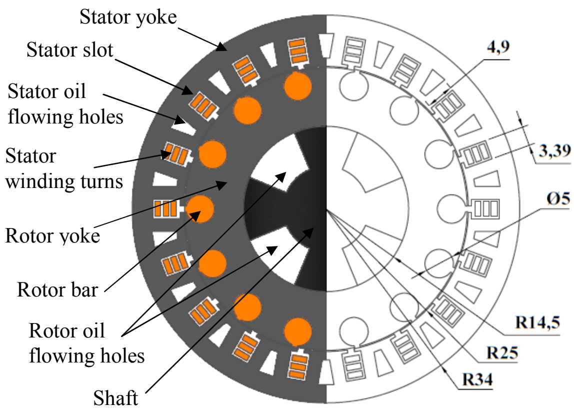

Figure 1: Cross Section View

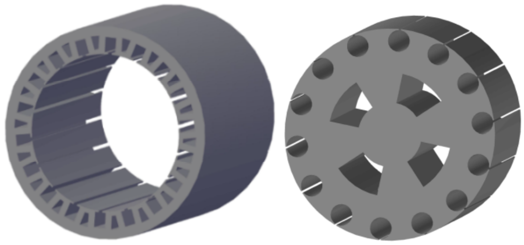

Figure 2: 3D Views

FEM SIMULATION

During the last two decades, the FEM-based simulation became a very useful tool in design and optimization of the new industrial products. In the electrical machines domain, this numerical method allowed to put in view intimate electromagnetic phenomena, which shortened and improved the design process. Depending on expected results, the simulation implies different approaches. In this paper, steady-state and transient analyses on 2D and multilayer structures are presented.
For this purpose, the commercial packages of the FLUX2D software are used
A. 2D Steady-State Simulation. This approach is a circuit-coupled analysis, which usually is performed in a repetitional way for different rotor speeds. The main results are presented in Figures 3,4 and 5 and correspond to straight rotor bars, open rotor slots and Vacoflux 50 laminated silicon steels.

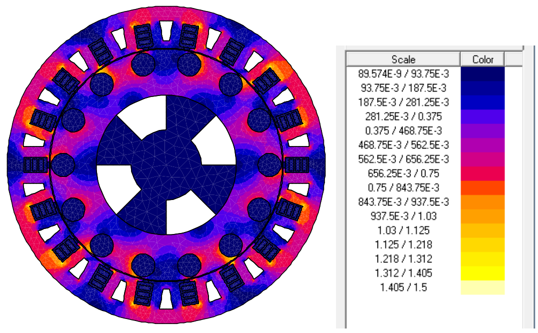

Figure 3: Flux Density Color Map-Vacoflux50

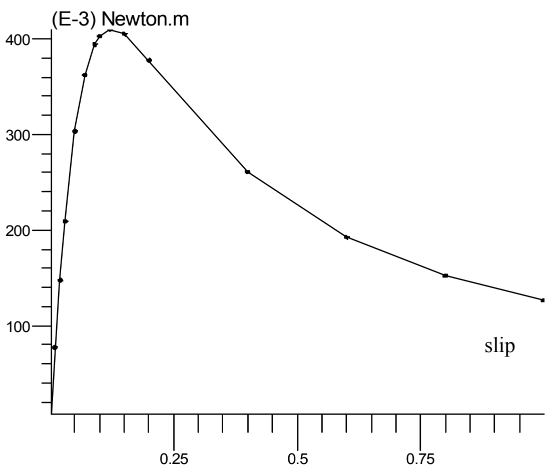

Figure 4: T = f(s) Characteristic

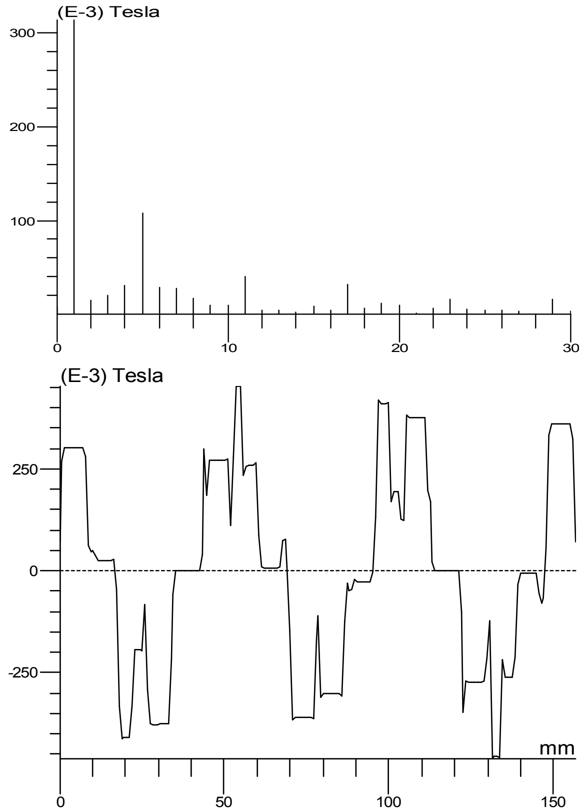

Figure 5: Flux Density Air-gap and Harmonics

The flux density color map shows the absence of any saturation region in the magnetic circuit at rated operation. Of great importance is the air-gap flux density and its content in high order harmonics. The fundamental value is of 0.32 T, which is rather low but expectable for a fractional power motor. There are also significant high order harmonics and the 5^{th} has unacceptable amplitude. This is the consequence of the number of slots adopted for the rotor. Finally, the T=f(s) curve gives information on the motor output capabilities. The rated torque corresponds to a slip value of s=0.028 (4860 r/min) and the breakdown torque has the value T_{max}=0.41 N·m for s_{max}=0.12. From this point of view, the target values are achieved.
Interesting results give the analysis that replaces the superior Vacoflux 50 with Vacoflux 17, Figures 6, 7, 8, 9 and 10.

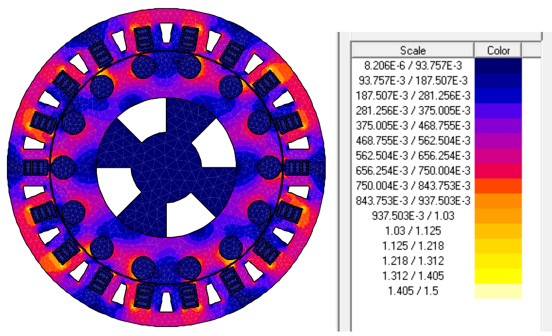

Figure 6: Flux Density Color Map-Vacoflux 17

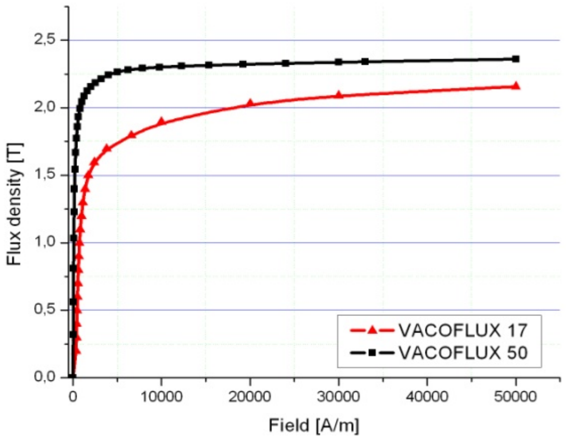

Figure 7: Magnetization Curves

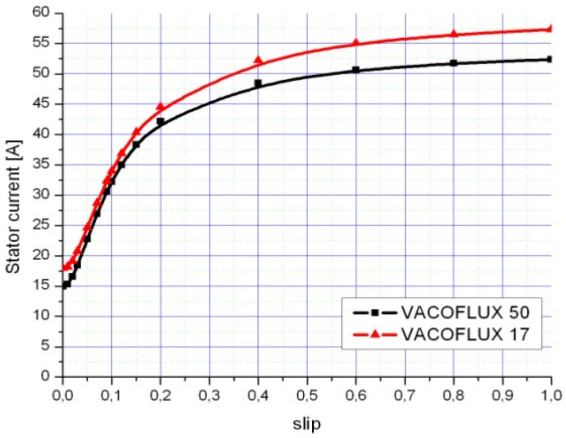

Figure 8: Stator Current versus Slip Variation

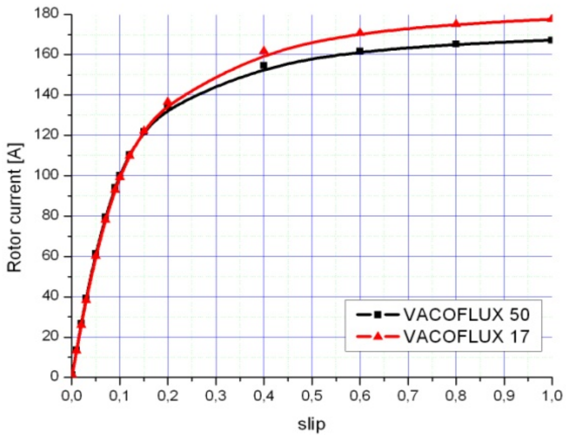

Figure 9: Rotor Current versus Slip Variation

The differences are significantly mainly on start-up, but has to be mentioned the higher stator current due to its magnetizing component. It produces supplementary winding losses and a rise in temperature. On the other side, the flux density color map shows superior values, which determine higher iron losses. Consequently, it is justified the use of a premium magnetic material.

The influence of the closed rotor slots is presented in Figures 11, 12 and 13. In this topology, two factors have a bad influence upon the machine performance.

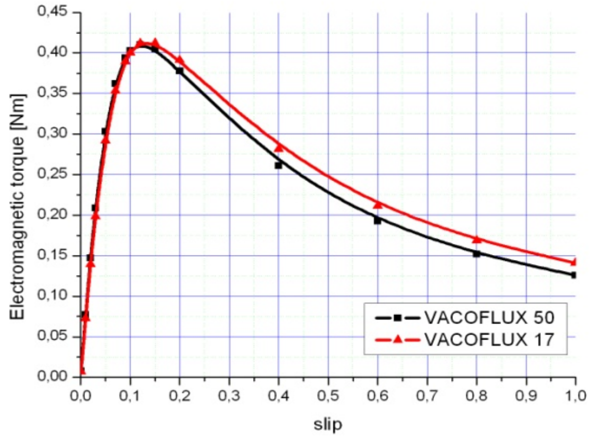

Figure 10: Torque Characteristic

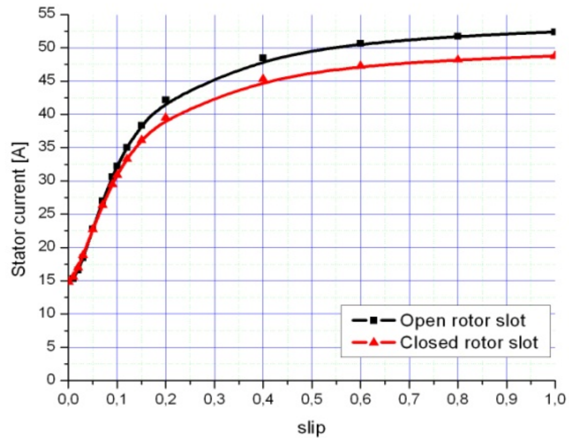

Figure 11: Stator Current versus Slip Variation

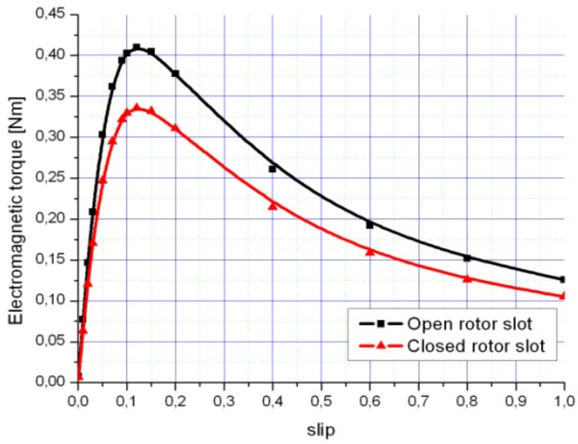

Figure 12: Torque Characteristic

The presence of the ferromagnetic bridge between rotor slots and outer rotor diameter gives free way to magnetic field lines, which prefer a smaller path through rotor circuit. The phenomenon is amplified by the supply frequency, which is five times greater than industrial value. As consequence, the rotor is poorly penetrated by the magnetic flux and the developed torque is lower.

The significant differences in T=f(s) characteristic eliminate the closed slots option.

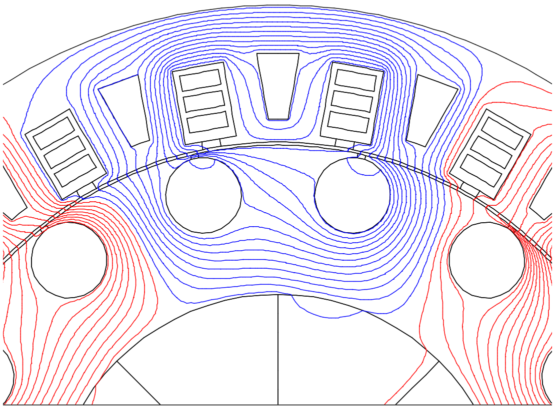

Figure 13: Flux Lines Distribution – Closed Slots

B. Multilayer Steady-State Simulation. This is a special approach destined for the analysis of axially skewed topologies. The machine is divided into pieces along the axial length and the FEM analysis operates only on the chosen sectional areas. Usually, the software is than capable to calculate the resultant. For our analysis, the motor has been divided in 5 slices. Figure 14 shows the electromagnetic load of the circuit by means of the flux density. There is a distortion (swinging) of the magnetic field due to the skew of the rotor bars. No saturation is present, as well.

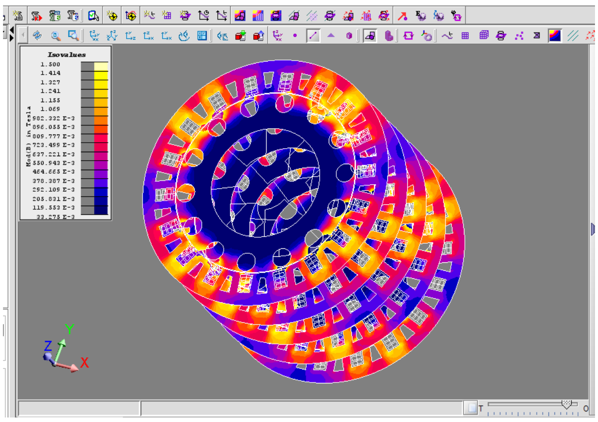

Figure 14: Flux Density Color Map - Multilayer

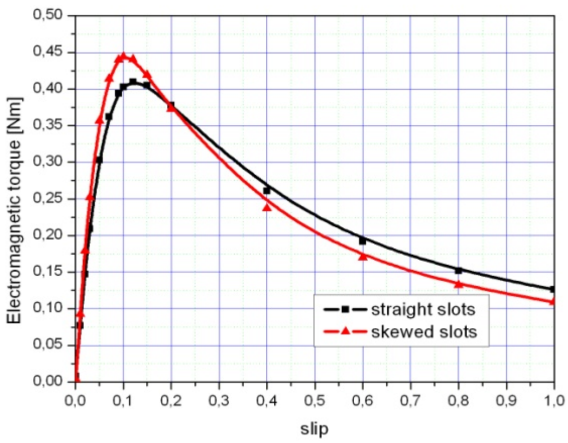

Figure 15: T = f(s) Characteristic

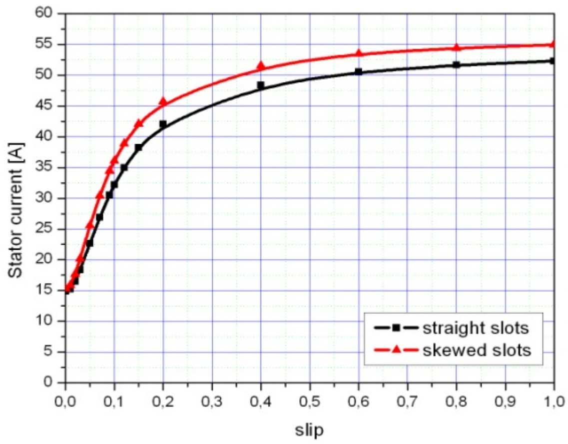

Figure 16: Statator Current versus Slip Variation

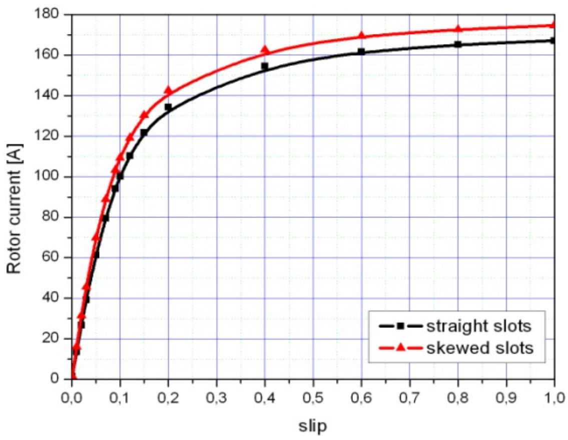

Figure 17: Rotor Current versus Slip Variation

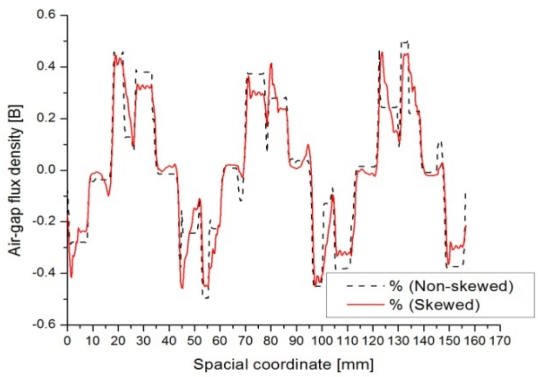

Figure 18: Air-gap Flux Density

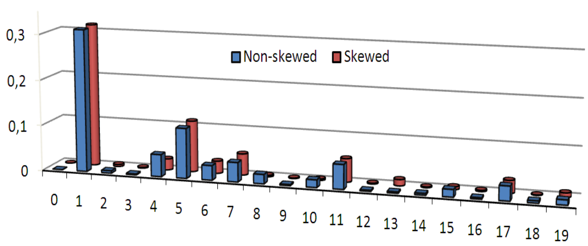

Figure 19: Fourier Analysis of the Air-gap Flux Density

The performance characteristics are presented together with the results corresponding to straight rotor slots structure in Figures 15, 16, 17 and 18.
As we expected, the torque characteristic is more favorable regarding rated slip and breakdown torque. There is, however, an increase in rotor and stator current values. Table 3 presents a comparison of the main parameters for straight and skewed rotor bars.

Table 3: Comparative Results

Straight bars	*Skewed bars*
T_{start}=0.127 N·m	T_{start}=0.121 N·m
T_{max}=0.41 N·m	T_{max}=0.44 N·m
s_{max}=0.12	s_{max}=0.1
s_{rated}=0.028 – 4860 r/min	s_{rated}=0.02 – 4900 r/min
I_{rated}=18 A – phase curr.	I_{rated}=18.2 A– phase curr.
I_{start}=52 A– phase curr.	I_{start}=55 A– phase curr.

C. Transient Simulation. This is a time-stepping analysis that takes into consideration the movement equation. In this paper, it has been simulated a start-up process when the motor is loaded with 0.09 N·m (approx. 50 % of rated load). The results are presented in Figures 20, 21, 22 and 23.

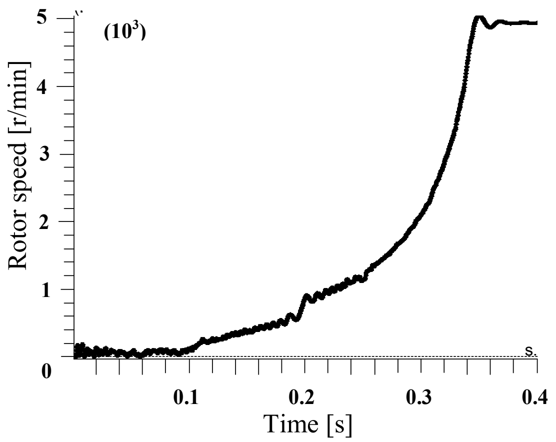

Figure 20: Speed Variation at Start-up – Straight Slots

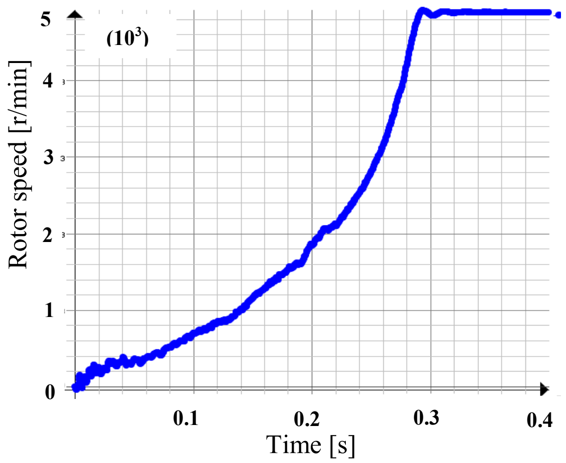

Figure 21: Speed Variation at Start-up – Skewed Slots

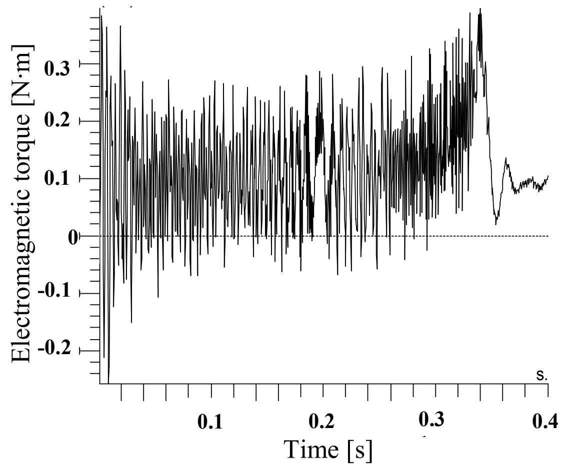

Figure 22: Torque Variation at Start-up – Straight Slots

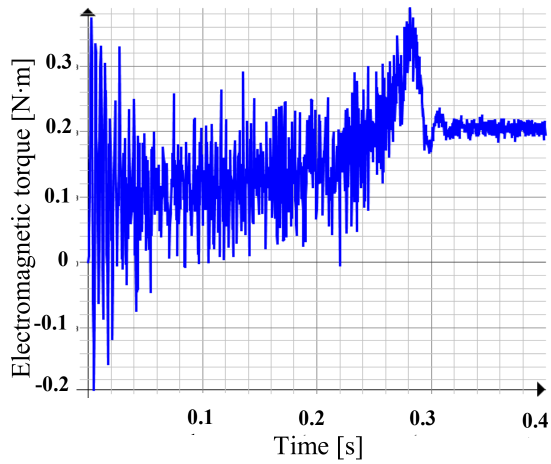

Figure 23: Torque Variation at Start-up – Skewed Slots

The motor with skewed rotor slots needs 0.3 seconds to finish the acceleration process while the machine with straight slots needs 0.37 seconds. Both speed and torque variations prove the superiority of the skewed machine.

CONCLUSIONS

The paper presents design considerations and FEM-based simulations of a fractional power three-phase induction motor. The severe constraints imposed by the customer requested multiple solution analyses in order to find an acceptable compromise. It has been investigated the influence of the rotor slots as regards their shape and inclination and the benefits of a superior magnetic material upon motor performance. The conclusions confirm the advantages but the drawbacks, as well, brought by the solutions that involve Copper rotor bars, skewed slots or closed/open slots in combination with high supply frequency. This study is useful in establishing some design directions for the fractional power motors.

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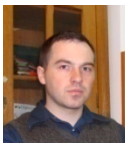

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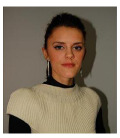

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