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Comparative FEM-based Analysis of Multiphase Induction Motor

This paper presents a comparative study of multiphase induction motor, which has alternately three-, five- and six-phase stator winding. The machine has been designed particularly for this purpose and has individual ring coils placed in each stator slot. The study consists in FEM analyses and mainly looks for the particularities of magnetic quantities such as air-gap flux density and electromagnetic torque.

Keywords: multiphase induction motor, FEM analysis

1. Introduction

The use of multiphase induction motors became lately more and more a viable solution for electric drives of various applications. If initially they have been used mostly in ship propulsion and aviation [1], [2], now there are new domains such as electric traction or wind-based electricity generation that inquire for these motors. Multiphase machines designate the electric machines with more than three phases. The prevalent types have five or six phases but machines with 12 or 15 phases are also popular. The multiphase machines have several advantages in comparison to the three-phase counterpart. It is about a higher torque density, reduced torque ripple and fault-tolerant capability, which allow the operation of the machine in absence of one or two phases with minimum of performance derating [1]-[3]. Moreover, a decrease of about 5% of the stator copper loss [2] with the increase of the phase number represents an advantage of the multiphase motors.

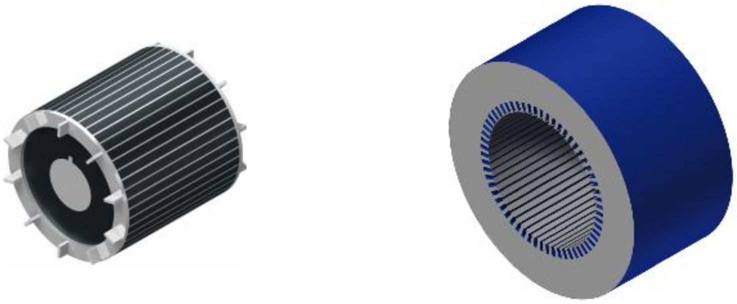
To this end, we decided to perform an analysis of the performance developed by the induction motor when it operates under three, five and six-phase structure. For this purpose a FEM-based software package is used and consequently, the results refer mainly to electromagnetic quantities. The study takes into consideration both magnetodynamic (which refers to steady-state operation) and transient (start-up) analyses.

2. Design and specific features of induction motor.

In order to run a comparative analysis, which requires a significant number of common elements, the design of the motor started somehow unusual by imposing the usual rated parameters (power, voltage, frequency, speed – see Table 1), but also the number of stator slots (Z_1). We had in mind a stator winding with an integer value of the number of slots per pole and per phase (q) for all three variants. Since the well-known expression is $Z_1=2p\cdot m_1\cdot q$, where p is the number of pole pairs and m_1 is the number of phases, then the minimum number of stator slots is $Z_1=60$. Table 2 presents the main geometrical parameter of the motor and Figure 1, a general view of the dismantled rotor and stator.

Table 1.

Parameter	Value
Output power, P_n	75 kW
Line voltage (Y connection)	750 V
Frequency	50 Hz
Pole number	2
Rated torque	245 Nm
Rated line current	67 A



Rotor Stator

Figure 1. Motor geometry.

Table 2.

Parameter	Value
Outer stator diameter, D_{1ex}	350 mm
Inner stator diameter, D_{1in}	215 mm
Length, L	200 mm
Air-gap width, δ	0.55 mm
Outer rotor diameter, D_{2ex}	213.9 mm
Inner rotor diameter, D_{2in}	160 mm
Stator slots number	60
Rotor slots number	48
Number of turns per coil	6

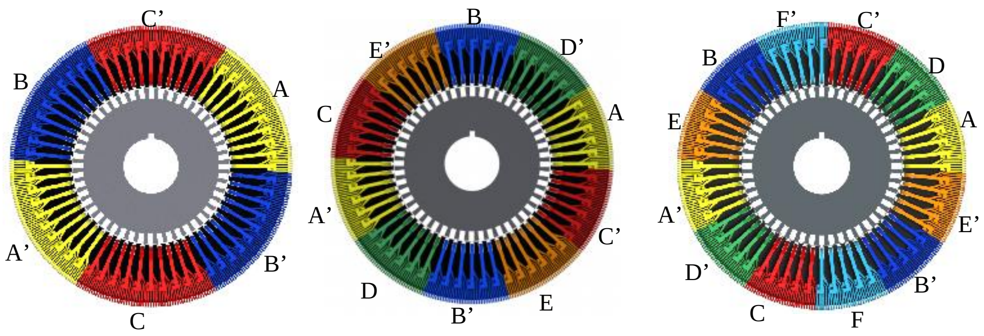
The most "delicate" issue of the design process consists in stator winding structure. Previous research reports show the particularities of multiphase windings [4]. Our motor is somehow special since it must equally offer the possibility of obtaining the three variants, which means:

- three phases 120° electrical degrees shifted in space;
- five phases 72° electrical degrees shifted in space;
- six phases 60° electrical degrees shifted in space.

A picture of the position of the phases on the periphery of the stator is presented in Figure 2.a. remark has to be made for the six-phase machine. Since the stator winding is a single layer one, it is impossible to build the regular structure, which involves two three-phase systems placed in opposition (180° electrical degrees of space lagging). We have adopted a second solution, often used in supply of the six-phase motors by means of frequency converters, which implies a 30° displacement of the two systems.

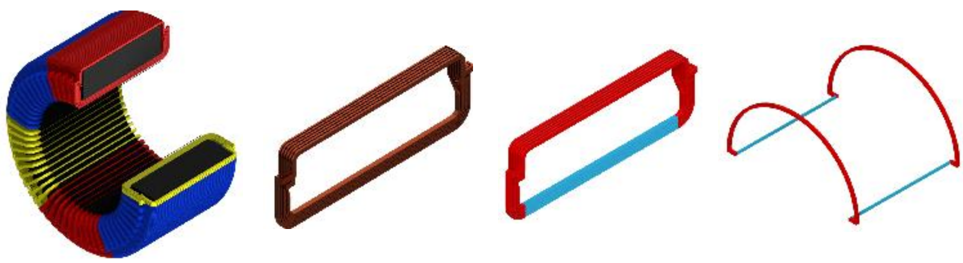
The obtaining of the three variants is practically impossible (or is very complicated) if the stator has a lap winding. On the contrary, if the winding is a ring one with individual coils placed in the slots, then different connections can be easily done and the achieving of any type of structure is feasible. Practically, the ring winding eliminates the concept of “winding pitch”. As consequence, the stator winding of our motor contains 60 ring coils made of 6 turns, Figure 3.a.

Usually the use of ring coils is avoided since one considers that the length of active parts in comparison to frontal (inactive) parts is smaller (Figure 3b) and the copper consumption is not effective. However, particular structures prove the contrary. When the magnetic circuit has a much higher diameter in comparison to its length and the machine has a lower number of poles (for example 2p=2 but sometimes even 2p=4) then the frontal parts become longer for a lap winding [5]. In our case, for example, a calculus proved that the ring coils have a frontal part 23% shorter than lap winding.



3-phase 5-phase 6-phase

Figure 2. Stator winding configuration.



a. Ring coil and stator cross-section b. Active part of ring and lap coils

Figure 3. Details on stator winding.

3. FEM-study results and discussion.

The Finite Element Method (FEM or FEA) is the numerical method most used in the simulation of electrical machines. The sensitivity of this method is very high and the results can be very close to the experimental ones. In other words, a proper analysis followed by an optimization procedure can offer the final solution for the construction of an electric machine.

The first approach took into consideration the so-called magnetodynamic analysis. It simulates the steady-state operation. Practically, this is a circuit-coupled analysis, which does not take into consideration the movement equations.

A special remark has to be made concerning the electric circuit. In order to ensure equal operation prerequisites (for a proper comparison), the supply voltage corresponding to each coil has been maintained constant. Since the line voltage (star connection) of the three-phase machine is of 750 V then we have the following phase voltages: U_{3ph}=433V, U_{5ph}=259.8V and U_{6ph}=216.5V.

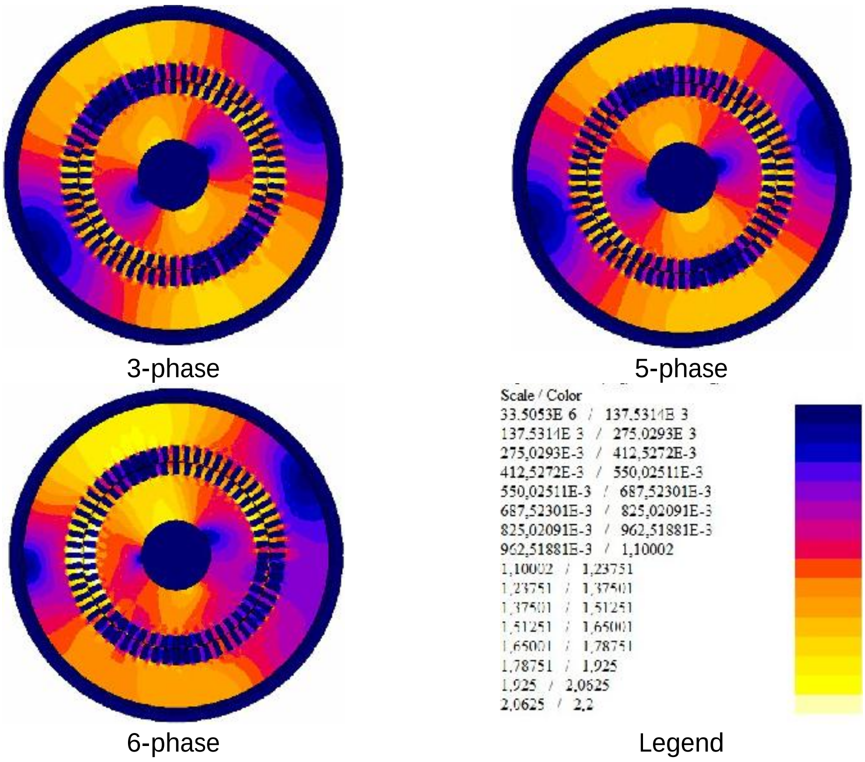


Figure 4. Flux density color map.

Figure 4 shows the flux density map inside the magnetic circuit. As one expected, the values should be similar for all three variants. However there is an obvious abnormality for the six-phase machine, which develop a non-symmetrical magnetic field. As a matter of fact, the particular supply (the above mentioned

30°) in absence of the control of phase currents determines a distortion of the rotating field.

The variation of the electromagnetic torque with slip is presented in Figure 5. One can see that both the starting torque and the pull-out torque have superior values with the increase of the number of phases.

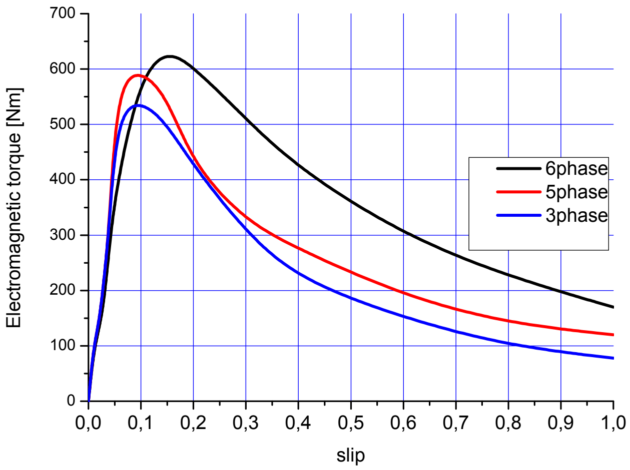


Figure 5. Variation of electromagnetic torque with slip.

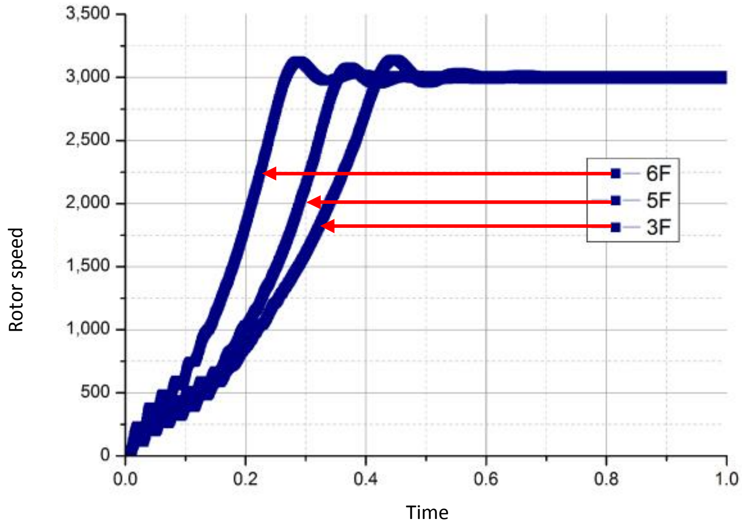


Figure 6. No-load start-up (transient duty).

The transient analysis adds the movement equation to the general equations system. Figure 6 put in view the no-load start-up and prove that, in accordance with the obtained start-up torque values there is a difference in acceleration of the motor, in favors of multiphase units.

4. Conclusion

We have investigated in this paper an induction motor that was supplied in three-, five- and six-phase configuration. For this purpose, a special design regarding the stator winding has been performed. The results confirm the superiority of multiphase motors in comparison to the three-phase counterparts.

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