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Franck SCULLER, Eric SEMAIL, Jean-Frederic CHARPENTIER, Stéphane CLENET -
Comparizon of Conventional and Unconventional 5-phase PM Motor Structures for Naval
Applications - IASME TRANSACTIONS - Vol. 1, n°2, p.365-370 - 2004

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Comparison of conventional and unconventional 5-phase PM motor structures for naval applications

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Abstract: - Multi-phase motors are widely used in marine propulsion. In this paper, a Multi-machine modeling of Surface Mounted PM motors is presented and applied to a 5-phase machine. The latter is proved to be equivalent to a set of two-phase fictitious machines each ones being characterized by a set of specific harmonic ranks. A simple control consists of supplying each fictitious machine with a current which contains only one harmonic. A five phase machine is then supplied by currents with only first and third harmonics. Considering this kind of control, it is shown that for a given stator resistance and average torque the Joule losses and the torque ripple are minimized if a simple criterion on the harmonics of electromotive force at constant speed is fulfilled. Different structures of rotor are then compared to examine numerically which improvements can be practically obtained.

Key-Words: - marine application, multi-phase PM motor, multi-machine, design.

1 Introduction

Electric marine propulsion widely uses multi-phase motors because of reliability, smooth torque and partition of power. Usually supplied by Pulse Amplitude Modulation Current Source Inverter (PAM CSI), these motors can nowadays be controlled by Voltage Source Inverter (VSI) thanks to advances in power semiconductors (IGBT, IGCT) and Digital Signal Processor (DSP)[1,2,3]. This kind of supply increases the flexibility of control. Studies [4,5,6,7] exhibit potential improvements on multi-phase induction motors. Multi-phase PM synchronous motor are also used [2,8,9]. The permanent excitation due to permanent magnets gives another design freedom degree. To find control laws [10], and also criteria of drive design, a vectorial multi-machine model of multi-phase motor is presented [11]: a multi-phase machine is equivalent to a set of 1-phase and 2-phase machines. In the paper, this approach enables, for a chosen supply strategy and a chosen stator, the definition of a criterion for the design of PM motor rotor with minimum Joule losses, under constraint of given average torque value. This criterion is used to find unconventional motor structures which can be very advantageous for this kind of application.

2 Multi-machine modeling of a multi-phase machine

2.1 Assumptions and notations

Usual assumptions are used to model the machine:

- All phases are identical and regularly shifted by an angle:

$$\alpha = \frac{2\pi}{n} \quad (1)$$

- Effects of saturation and damper windings are neglected;

All quantities relating to the phase k are written x_k .

The n -phase machine is described in figure 1.

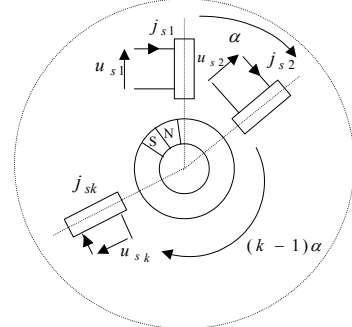


Fig.1: Presentation of n -phase synchronous machine

2.2 Usual modeling in a natural base

In the usual matricial approach of n -phase electric machines, a vector n -space is implicitly considered since vectors with n lines are defined. This space is provided with an orthonormal base $B_n = \{\overline{x_1^n}, \overline{x_2^n}, \dots, \overline{x_n^n}\}$ that can be called “natural” since the coordinates of a vector in this base are the measurable values relative to each phase.

In this paper, this space is considering to be an Euclidean vectorial space with the usual canonic dot product.

In this natural base, different vectors are defined:

$$\bullet \vec{u}_s = u_{s1} \vec{x}_1^n + u_{s2} \vec{x}_2^n + \dots + u_{sn} \vec{x}_n^n \quad (2)$$

$$\bullet \vec{j}_s = j_{s1} \vec{x}_1^n + j_{s2} \vec{x}_2^n + \dots + j_{sn} \vec{x}_n^n \quad (3)$$

$$\bullet \vec{\phi}_s = \phi_{s1} \vec{x}_1^n + \phi_{s2} \vec{x}_2^n + \dots + \phi_{sn} \vec{x}_n^n \quad (4)$$

$$\bullet \vec{e} = e_1 \vec{x}_1^n + e_2 \vec{x}_2^n + \dots + e_n \vec{x}_n^n \quad (5)$$

where :

- ϕ_{sk} is the flux through the phase k exclusively produced by the stator currents ;
- e_k is the electromotive force (EMF) induced in the phase k only due to the rotor magnets.

Taking into account R_s , the stator resistance per phase, the vectorial voltage equation is:

$$\vec{u}_s = R_s \vec{j}_s + \left[\frac{d\vec{\phi}_s}{dt} \right]_{/B_n} + \vec{e} \quad (6)$$

The B_n index indicates that the differentiation is operated according to the B_n natural base.

This equation can be projected onto each vector of the natural base to find again the more usual equation:

$$u_{sk} = \vec{u}_s \cdot \vec{x}_k^n = R_s j_{sk} + \frac{d\phi_{sk}}{dt} + e_k \quad (7)$$

Using the assumptions previously defined, a linear relation between the stator currents vector and the stator flux vector can be written as:

$$\vec{\phi}_s = L_s (\vec{j}_s) \quad (8)$$

usually with the matrix notation:

$$[L_s^n] = \text{Mat}[L_s, B_n] = \begin{pmatrix} L_{ss1} & M_{s_1s_2} & \dots & M_{s_1s_n} \\ M_{s_2s_1} & L_{ss2} & \dots & M_{s_2s_n} \\ \dots & \dots & \dots & \dots \\ M_{s_ns_1} & M_{s_ns_2} & \dots & L_{ssn} \end{pmatrix} \quad (9)$$

The modeling of the machine in the natural base is not simple due to the complexity of the matrix $[L_s^n]$. It would be interesting to find a simpler form for matrix L_s .

2.3. Vectorial decomposition in eigenspaces of L_s

Equation (9) is true whatever the chosen base associated with the stator coils. The symmetry of the inductance matrix $[L_s^n]$ states that:

- there exists F eigenspaces E_g associated with the F eigenvalues of L_s ;
- the dimension of the eigenspace E_g is equal to the multiplicity of eigenvalue L_g ;
- the eigenspaces are orthogonal each others.

Then, every vector \vec{y} of \square^n can be decomposed into a sum of vectors as \vec{y}_g with $\vec{y}_g \in E_g$:

$$\vec{y} = \sum_{g=1}^{g=F} \vec{y}_g \quad (10)$$

\vec{y}_g is easily obtained by orthogonal projection onto E_g .

Moreover, as L_g are eigenvalues of L_s , a simpler expression between flux and currents is obtained:

$$\vec{\phi}_s = \sum_{g=1}^{g=F} \vec{\phi}_g = \sum_{g=1}^{g=F} L_g \vec{j}_g \quad (11)$$

2.4 Multi-machine concept

It is now possible to show that the torque of a multi-phase machine can be decomposed into the sum of the torques of machines which are magnetically decoupled. At first, the electric power in the stator is expressed:

$$p_s = \sum_{k=1}^{k=n} u_{sk} j_{sk} = \vec{u}_s \cdot \vec{j}_s \quad (12)$$

With expression (6) we obtain:

$$p_s = \vec{u}_s \cdot \vec{j}_s = R_s \vec{j}_s \cdot \vec{j}_s + \left[\frac{d\vec{\phi}_s}{dt} \right]_{B_n} \cdot \vec{j}_s + \vec{e}_s \cdot \vec{j}_s \quad (13)$$

The first term is related to stator Joule losses.

With the previous assumptions, the eigenvalues and eigenvectors are constant and electromotive force do not depend on currents. This gives:

$$\left[\frac{d\vec{\phi}_s}{dt} \right]_{B_n} = \sum_{g=1}^{g=F} L_g \frac{d\vec{j}_g}{dt} \text{ and } \vec{e} = \left(\frac{d\theta}{dt} \right) \frac{d\vec{\phi}_{sr}}{d\theta} \text{ where}$$

$\vec{\phi}_{sr}$ the flux vector due to the field created by the rotor.

Therefore, as the eigenspaces are orthogonal to another, expression (13) becomes:

$$\begin{aligned} p_s = \vec{u}_s \cdot \vec{j}_s &= \sum_{g=1}^{g=F} \left(R_s (\vec{j}_g)^2 + L_g \frac{d\vec{j}_g}{dt} \cdot \vec{j}_g + \left(\frac{d\theta}{dt} \right) \frac{d\vec{\phi}_{sr}}{d\theta} \cdot \vec{j}_g \right) \\ &= \sum_{g=1}^{g=F} \left(R_s (\vec{j}_g)^2 + \frac{1}{2} \frac{d(L_g (\vec{j}_g)^2)}{dt} + \left(\frac{d\theta}{dt} \right) \frac{d\vec{\phi}_{sr}}{d\theta} \cdot \vec{j}_g \right) \end{aligned} \quad (14)$$

The first term can be considered as stator Joule losses, the second term as the derivative of stator magnetic energy and the third as the product of angular speed $d\theta/dt$ and torque:

$$C_g = \frac{d\overrightarrow{\phi_{srg}}}{d\theta} \cdot \overrightarrow{j_g} \quad (15)$$

Thus the total torque is:

$$C = \sum_{g=1}^{g=F} C_g \quad (16)$$

F fictitious machines can be considering, each one is associated with an eigenspace. These machines are magnetically independent and the number of phases of each one is equal to the dimension of its associated eigenspace.

2.5 Harmonic Characterization of fictitious machines

It is now interesting to characterize these fictitious machines to be able to control and supply them correctly.

Expression (15) shows that the torque C_g is the dot product of the vectorial projections of two vectors. The first one is the stator current vector, which is imposed by the power supply. The second one that depends on the design of the machine is:

$$\overrightarrow{\varepsilon} = \frac{d\overrightarrow{\phi_{sr}}}{d\theta} \quad (17)$$

This vector $\overrightarrow{\varepsilon}$ corresponds to the back EMF for a 1 rad/s speed and can be called “elementary EMF vector”.

As it is a $2\pi/p$ periodic function, it can be expanded into a Fourier series and consequently expressed as a sum of vectors associated with harmonic order number k . Properties of symmetry, due to the regular manufacturing assumption, involve, as usual, the cancellation of cosine terms and of even sine terms.

Moreover, when a vector linked to a harmonic is projected into an eigenspace, then the result is not the same depending on the number of harmonic rank. Depending on the considered eigenspace associated with the fictitious studied machine, the null terms of the Fourier serie are not the same. There is a distribution of the different harmonics between the eigenspaces. This particularity is verified for every vector which has the same mathematical properties as $d\overrightarrow{\phi_{sr}}/d\theta$. Thus, it is possible to associate each fictitious machine with a characteristic family of harmonics.

For 5-phase and 7-phase Table 1 and Table 2 describe the decomposition.

Fictitious machine	Families of harmonics
First 2-phase machine	1, 9, 11, ..., $5h \pm 1$
Second 2-phase machine	3, 7, 13, ..., $5h \pm 3$
1-phase machine	5, 15, ..., $5h$

Table 1 : Harmonic characterization for 5-phase machine

Fictitious machine	Families of harmonics
First 2-phase machine	1, 13, 15, ..., $7h \pm 1$
Second 2-phase machine	3, 11, 17, ..., $7h \pm 5$
Third 2-phase machine	5, 9, 19, ..., $7h \pm 5$
1-phase machine	7, 21, ..., $7h$

Table 2 : Harmonic characterization for 7-phase machine

3. Multi-machine design strategy.

3.1 Assumption on supplying strategy

The aim of this study is to look at several structures of PM five-phase machine with a supply strategy based on the multi-machine concept. With this approach, the current is controlled with a PMW multi-leg inverter in each of the fictitious machines.

A simple control consists of supplying each fictitious machine with a current which has only one harmonic[10]. For example, to supply the two 2-phase fictitious machines of a 5-phase PM machine, the current in phase k must be a sum of two harmonics, the first and the third i.e.:

$$j_{s_k} = f_{j_s,1} \sin(\omega t - (k-1)\frac{2\pi}{5}) + f_{j_s,3} \sin(3(\omega t - (k-1)\frac{2\pi}{5})) \quad (18)$$

3.2 Supplying strategy for a given fictitious machine

The aim of the presented work is to minimize the Joule losses for a given performance in terms of electromagnetic torque (average value C_f and torque ripple).

The torque is the dot product of elementary EMF vector and the current vector:

$$C = \overrightarrow{\varepsilon} \cdot \overrightarrow{j_s} \quad (19)$$

In order to use the multimachine concept, the Fourier decomposition of elementary EMF must be calculated :

$$\varepsilon_k = \sum_{m=0}^{+\infty} f_{\varepsilon,m} \sin(m(\omega t + \varphi - (k-1)\frac{2\pi}{5})) \quad (20)$$

with φ being the out of phase of elementary EMF versus current.

Next, by considering (15) and table 1, average torque of the two fed fictitious machines can be calculated :

$$\langle C_1 \rangle = \frac{5}{2} f_{j_s,1} f_{\varepsilon,1} \cos(\varphi) \quad (1st_machine)$$

$$\langle C_2 \rangle = \frac{5}{2} f_{j_s,3} f_{\varepsilon,3} \cos(3\varphi) \quad (2nd_machine)$$

If $\varphi = 0$ (maximum torque strategy), according to (16), the global average torque is

$$\langle C \rangle = \frac{5}{2} [f_{j_s,1} f_{\varepsilon,1} + f_{j_s,3} f_{\varepsilon,3}] = \frac{5}{2} \overline{f_{j_s,13} \cdot f_{\varepsilon,13}} \quad (22)$$

with $\begin{cases} \overline{f_{j_s,13}} = [f_{j_s,1}, f_{j_s,3}] \\ \overline{f_{\varepsilon,13}} = [f_{\varepsilon,1}, f_{\varepsilon,3}] \end{cases}$

Therefore the Joule losses can be expressed as a function of the statoric resistance R_s and the square of $\overline{f_{j_s,13}}$ norm.

$$P_j = \langle R_s \overline{j_s} \cdot \overline{j_s} \rangle = \frac{5R_s}{2} \|\overline{f_{j_s,13}}\|^2 \quad (23)$$

Finding the best current distribution between the two fictitious machines for a given motor topology and for a given average torque ($\overline{f_{\varepsilon,13}}$, R_s and C_f are fixed) can be formulated as the following optimization problem :

- optimization variables : $\overline{f_{j_s,13}} = [f_{j_s,1}, f_{j_s,3}]$
- objective : to minimize $P_j = \frac{5R_s}{2} \|\overline{f_{j_s,13}}\|^2$
- constraint : $5 \overline{f_{\varepsilon,13}} \cdot \overline{f_{j_s,13}} = 2C_f$

This problem has a single solution that can be easily shown to be:

$$\overline{f_{j_s,13}}^* = \frac{2C_f}{5 \|\overline{f_{\varepsilon,13}}\|^2} \overline{f_{\varepsilon,13}} \quad (24)$$

That means that the value of the current harmonics that corresponds to each fictitious machine must be proportional to the corresponding harmonics of the EMF. The corresponding Joule losses are given by

$$P_j^* = \frac{2R_s C_f^2}{5 \|\overline{f_{\varepsilon,13}}\|^2} = \frac{2R_s C_f^2}{5(f_{\varepsilon,1}^2 + f_{\varepsilon,3}^2)} \quad (25)$$

With the supply strategy defined in paragraph 3.1, the other harmonics of the elementary EMF vector generate pulsating torques which do not contribute to the average value of the torque. To have a constant torque the other harmonics of each fictitious fed machine family must be minimized in the elementary EMF (for a 5 phase that means that the 7th, 9th and 11th harmonics of the EMF must be very small).

3.3 Machine rotor design criterion.

We consider the same stator topology and windings for all the studied PM machines : same iron topology, number of pole pairs, winding distribution (conventional distributed winding with polar step) and same air gap value. That means that the resistance R_s is fixed and that the values of the elementary EMF are related by the rotor topology. So the best rotor configuration in terms of losses corresponds to the minimal value of P_j^* in eq. (25). This configuration corresponds to the maximal value for the norm of $\overline{f_{\varepsilon,13}}$ vector (that contains the first harmonic of each fed machine).

For a 5-phase PM machine supply using the assumptions presented in paragraph 3.1, it corresponds to the maximal value of $f_{\varepsilon,1}^2 + f_{\varepsilon,3}^2$. Furthermore to minimize the torque ripple due to the pulsating torques harmonic 7,9 and 11 of elementary EMF must be also minimized.

4. Study of several PM motor structures

4.1 Studied structures common parameters

This work studies and compares several structures of Surface Mounted Permanent Motor using the design criterion presented in the previous section. The considered machine have the same stator configuration. The rotor configuration also corresponds to a common set of parameters: same magnet volume, same magnet material and magnetization. The required torque corresponds to the specifications of a small podded propeller. The considered common parameters (stator and rotor) are given in Table 3.

4.2 Performance characterization and validation

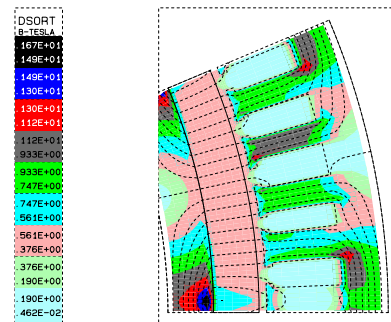


Fig.2: Magnetic flux density distribution in a conventional case

The elementary EMF of each studied machine are calculated using a 2D Finite Difference Field

calculation software (DIFIMEDI) [12]. This tool enables the validation of the presented choices with a good accuracy. As an example the magnetic flux density distribution for radial magnets with a pole pitch of 180 electrical degrees is given in fig. 2 (1 pole).

Number of phases	N = 5
Number of pole pairs	P = 8
Stator core thickness	Th = 6 mm
Air gap	e = 1 mm
Angular teeth width	Wt = 2.25 degrees
Axial machine length	L = 35 cm
Bore Diameter	D = 166 mm
Slot depth	Ds = 1 cm
Total number of slot	Ns = 80 (1slot/phase/pole)
Number of conductors/slot	20
Slot fill factor	0.5
Statoric resistance	Rs = 1.2 Ohms
Required average torque	60N.m (100 to 500rpm)
Power at 500rpm	3.1 kW
Magnet total volume	1042 cm ³ (almost 6 kg)
Magnet material	NeFeB Isotropic Bonded magnet
Magnet Magnetization	0.6 T

Table 3: machine common parameters set

4.3 Presentation of the 2 studied rotor designs.

In this paper 2 kinds of rotor design are presented. The first one is the classical structure with a radial magnet over all the pole pitch. In the second one each pole is made of 3 magnets which are magnetized in unconventional magnetization directions. In both cases the magnets are stuck on the surface of the iron rotor core. The second kind of rotor can be easily made with bonded isotropic Rare earth magnets. Both rotors structures are shown in fig. 3. In the second configuration the widths and orientations of the magnets have been chosen in order to maximize the 1st and 3rd harmonics and to minimize the 7th, 9th and 11th harmonics of the elementary EMF. In figure 3 the waveforms of the elementary EMF for the 2 kinds of design are shown. The corresponding harmonic magnitudes amplitude are presented in table 4.

Rotor type	Conventional design	Unconventional design
1 st harmonic	5,250 V	5,610 V
3 rd harmonic	1,460 V	1,780 V
5 th harmonic	0,697 V	0,530 V
7 th harmonic	0,417 V	0,056 V
9 th harmonic	0,295 V	0,024 V
11 th harmonic	0,110 V	0,073 V

Table 4: EMF harmonic magnitudes

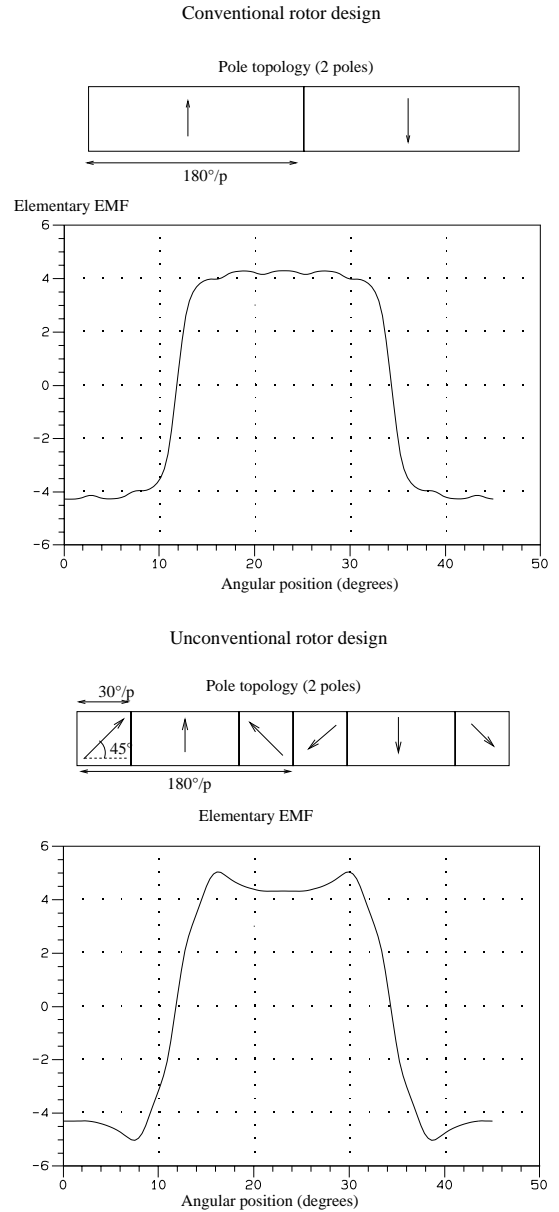


Fig.3: Elementary EMF waveform for the 2 rotor design

5.2 Results

The first kind of structure considered is a conventional radial rotor with a sinusoidal current supply. In a second approach this classical machine is supplied using the strategy presented at paragraph 3.1. The required current level (first harmonic and third harmonic), the corresponding Joule losses and torque ripple are given in the first line of Table 4. The third EMF harmonic of this machine is around 25% of the first one. So with the strategy defined in part 3.1 the Joule losses have been reduced worth 5% for the same average torque (Table 5). We can also notice that for both cases the EM torque ripple is important. This phenomenon is due to the pulsating torques caused by the 7th and 9th harmonics of EMF.

Next a second kind of rotor is considered. This unconventional machine is supplied using the strategy presented at paragraph 3.1. The corresponding Joule losses, currents value and EM torque ripple values are given also in Table 5. It is noted that the Joule losses have been reduced by about 20%. The EM torque ripples have also been widely reduced : the 7th and 9th harmonics of the EMF are very small, so the pulsating torques related to these harmonics has been reduced. So the presented unconventional structure of machine associated with a multi-machine feeding current strategy seems to be a very interesting solution in terms of minimization of the Joule losses and torque ripple.

Rotor type	Feeding current strategy	Joule losses	EM torque ripple	Current first harmonic (RMS)	Current third harmonic (RMS)
Conventional (radial magnetization)	H1 only	63,0 W	4,3 N.m	3,25 A	0,00 A
	H1 and H3 (&3,1)	58,7 W	5,6 N.m	3,01 A	0,84 A
Unconventional (3 magnets/pole)	H1 and H3 (&3,1)	50,3 W	1,2 N.m	2,76 A	0,88A

Table 5: Results for a required torque of 60N.m

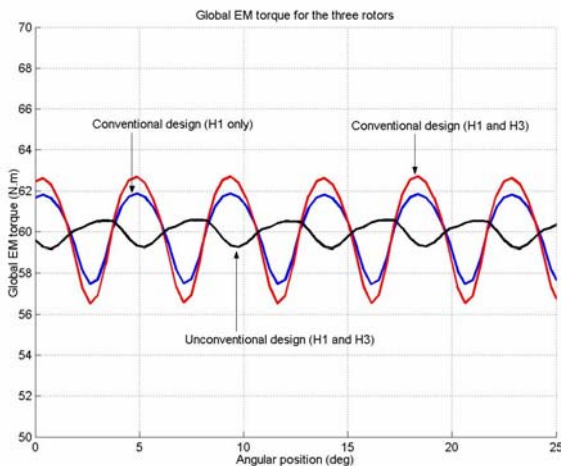


Fig.4: Global EM Torque for the 3 cases (60 N.m required)

4 Conclusion

In this paper several design configurations of Surface Mounted PM 5 phase motors fed by a PMW voltage inverter are studied using the association of a multi-machine modeling and a 2D Finite Difference field calculation software. This approach enables the determination of a design criterion to minimize the Joule's losses for a given performance in terms of torque. For a given common set of parameters and a given performance specifications, some conventional and unconventional structures of rotor are compared. This study shows that the choice of unconventional rotor configurations can be a very interesting choice to improve performances of multiphase SMPM machines.

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