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Multi-criteria based design approach of multiphase permanent magnet low speed synchronous machines

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Abstract

This paper presents a design methodology dedicated to multiphase Permanent Magnet Synchronous Machines (PMSM) supplied by Pulse Width Modulation Voltage Source Inverters (PWM VSI). Firstly opportunities for increasing torque density using the harmonics are considered. The specific constraints due to the PWM supply of multiphase machines are also taken into account during the design phase. All the defined constraints are expressed in a simple manner by using a multimachine modelling of the multiphase machines. This multimachine design is then applied in order to meet the specifications of a marine propeller: verifying simultaneously four design constraints, an initial 60-pole 3-phase machine is converted into a 58-pole 5-phase machine without changing the geometry and the active volume (iron, copper and magnet). Firstly, a specific fractional-slot winding, which yields to good characteristics for PWM supply and winding factors, is chosen. Then, using this winding, the magnet layer is designed to improve the flux focussing. According to analytical and numerical calculations, the five-phase machine provides a higher torque (about 15%) and less pulsating torque (71% lower) than the initial three-phase machine with the same copper losses.

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1 Introduction

Electrical marine propulsion commonly uses multiphase low speed motors whose power is greater than $1MW$. The number of phases, greater than three, is not only justified by the induced power partition between the different phases but also by a smoother torque and a higher fault tolerance. With the advances of Digital Signal Processors (DSP) and high power devices such as Insulated Gate Bipolar Transistors (IGBT), it is now possible to use PWM VSI for supplying high power propulsion machines [1]. The induction machines and the PMSM can be easily considered in this instance since the constraint on the reactive power does not apply [2].

PMSM with rare earth magnets are an expensive solution but present an even higher torque density than the induction machines, especially by making use of the harmonics of the electromotive force (emf) in the case of multi-phase machines. This point is very interesting for ship propulsion podded motors and for submarine motors [3]. Nevertheless, the torque ripples, of critical importance for low speed motors, become then more difficult to control because of the interactions of the current with the harmonics of the emf.

Even though, for cases where very high power values are used (greater than $10MW$), the use of multi-phase machines is still justified due to the distribution of power, this is not necessarily valid for medium power [4]. Of course, the tolerance to faults as in open-circuited phases is still higher with multiphase machines. On the contrary, the torque pulsations of the three-phase machines can be very low if they are controlled in the rotor d-q reference frame and if their emfs are sinusoidal [5]. If the emfs are not sinusoidal and a classical vector control with simple Intersective PWM is used, then interactions between emf harmonics and the fundamental of the current

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induce torque pulsations. One major advantage of multiphase PM machines is to alleviate this constraint related to sinusoidal emfs, by taken advantage of the harmonics of electromotive forces. The torque density (in Nm/m^3) can be higher than with three-phase sinusoidal machines while keeping the same quality of torque [6]. This offers new opportunities when determining the winding configurations [7, 8] and for the shapes of the Permanent Magnet.

This paper presents different criteria that are taken into account simultaneously for the design of a multiphase low speed PMSM in order to improve performance. Our work focuses on acting on the space harmonics whose interactions are different for a multi-phase machine in comparison with those of a three-phase machine. It has been shown, initially for particular multiphase machines with concentrated windings [9], and more recently for a wider family of n-phase machines [10] with N identical and regularly shifted windings, that families of space harmonics can be defined. These families do not interact amongst themselves.

The criteria of this methodology are firstly presented. This method is then applied to increase the performance of a $2.1MW$ podded propeller: the initial design using a three-phase PMSM is transformed into a five-phase one that fulfills all the specified criteria. The transformation is obtained by a small modification of the pole number and the use of fractional slot unconventional windings. The last part of the study shows that the motor performances can be improved further by changing the magnet layer. This change optimizes the use of the first and third emf harmonics to increase the torque density.

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2 Design approach for five-phase PM machines

2.1 Criteria to improve the torque density of a five-phase machine with references to a three-phase machine

In this subsection, our aim is to find a simple condition that ensures a torque density improvement when the phase number is changed from three to five, with the assumption of a perfect sinusoidal current. These two machines are assumed to have the same main geometrical specifications (same diameter) and to run with the same current density j_s, the same linear load A and the same active volume of copper V_{cu}. Consequently the copper sections S_{cu} are also equal. In other words, the two machines have the same active copper losses and the same thermal behaviour.

Given the perfect sinusoidal current assumption, the average electromagnetic torque provided by a N-phase machine results from the interaction of the phase current and the back-emf fundamental. The average torque $T^{avg}(N)$ is then equal to the product of the RMS value of the current $i^{RMS}(N)$ by the RMS value of the elementary back-emf $\epsilon^{RMS}(N)$:

$$T^{avg}(N) = N\epsilon^{RMS}(N) i^{RMS}(N) \cos(\psi) \tag{1}$$

In (1), ψ is the angle between the current and the back-emf. In (1), we can replace the RMS current density j_s and the conductor section $s_{cd}(N)$:

$$T^{avg}(N) = N\epsilon^{RMS}(N) j_s s_{cd}(N) \cos(\psi)$$

The conductor section $s_{cd}(N)$ is also the total copper section S_{cu} divided by

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the total number of conductors $n_{cd}(N)$:

$$T^{avg}(N) = j_s \frac{S_{cu}}{n_{cd}(N)} N \epsilon^{RMS}(N) \cos(\psi)$$

The total number of conductors $n_{cd}(N)$ can be expressed as the product of the phase number N by the number of conductors per phase $n_{cd/\phi}(N)$:

$$T^{avg}(N) = j_s \frac{S_{cu}}{N n_{cd/\phi}(N)} N \epsilon^{RMS}(N) \cos(\psi)$$

The elementary back-emf for a conductor $\epsilon_{cd}^{RMS}(N)$ is thus given by:

$$T^{avg}(N) = j_s S_{cu} \epsilon_{cd}^{RMS}(N) \cos(\psi) \tag{2}$$

Relation (2) allows us to define the condition necessary to obtain a higher average torque with a five-phase machine than with a three-phase machine. This condition, which we called (C1), is related to the associated elementary back-emf for a conductor:

$$\frac{T^{avg}(5)}{T^{avg}(3)} \geq 1 \quad \Leftrightarrow \quad \frac{\epsilon_{cd}^{RMS}(5)}{\epsilon_{cd}^{RMS}(3)} \geq 1 \tag{3}$$

With this condition (C1), the five-phase machine is guaranteed a higher average torque than the three-phase machine when using the classical sinusoidal supply strategy. Moreover, if the third harmonic current injection and the design strategy described in the next subsection are used, the performance becomes even better.

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2.2 Criteria based on the harmonic property of the multi-phase machines

In this paragraph, we define two criteria (C2) and (C3) that are directly linked with the presence of independent families of harmonics for a machine that fulfills the following assumptions [10]:

- the five phases are identical and regularly shifted
- saturation and damper windings are neglected
- the back electromotive force (back-EMF) in the stator windings is not disturbed by the stator currents.

For a wye-coupled five-phase machine, two families must be thus considered. One way to give a synthetic view of a multi-phase machine is to consider it as a set of two 2-phase fictitious machines noted M1 and M2, electrically and mechanically coupled, each characterized by its own cyclic inductance and back electromotive force. The total torque is the sum of the two elementary torques produced by the M1 and M2. Each elementary machine is associated with a particular family of harmonics (M1, 1^{st}, 9^{th}, $(10k \pm 1)^{th}$ harmonics; M2, 3^{rd}, 7^{th}, $(10k \pm 3)^{th}$ harmonics). As such, a simple but efficient vector control using a VSI can be implemented for this machine if the following appropriate criteria are satisfied during the design for the two fictitious machines:

- (C2): the two cyclic inductances λ_1 and λ_2 of the same order
- (C3): two sinusoidal electromotive forces.

To explain the origin of the (C2) criterium, let us note that if the machine has a pure sinusoidal mmf, then the cyclic inductance λ_2 of M2 is only

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determined by the leakage flux. As the time constants are $\tau_1 = \lambda_1/R_s$ and $\tau_2 = \lambda_2/R_s$, with R_s the stator resistance, it is easy to understand that the amplitude of the parasitic currents induced by the PWM will be limited by the choice of a high carrier-frequency. It is then convenient to design the machine in order to have the same order for the two cyclic inductances. To fulfill this objective, it is possible to act on the windings. Windings with magnetomotive forces of the same value for the first and third harmonics imply two identical cyclic inductances. Consequently, it is necessary to conceive adequate windings. The criterium (C3) regarding the electromotive force can be satisfied by changing the windings and the magnet layer.

Finally, a machine satisfying these two properties can then develop a perfectly constant torque when it is supplied by currents that contain only the first and the third harmonics. Thus the third harmonic of the emf contributes to a higher torque without additional torque ripples. It is possible to design machines that can rotate at very low speeds without vibrations induced by torque ripples. Of course, a fourth design criterium (C4) concerns the cogging torque.

3 Conversion of a three-phase machine into a five-phase machine

By considering the design of a podded propeller (2100 kW at 105 rpm), this section practically illustrates the benefits that can be expected when using these specifications with a phase number equal to 5 instead of 3. The specifications given in table 1 correspond to the characteristics of the reference three-phase propeller. All these characteristics remain invariant when the phase number is changed to 5. Particularly, iron, magnet and active cop-

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Table 1: Propeller characteristics

Effective length	1.125 m
Stator diameter D	1.6 m
Stator yoke thickness	0.05 m
Mechanical airgap g	0.005 m
Rotor yoke thickness	0.03 m
Magnet layer thickness	0.015 m
Remanent flux density B_r	1.17 T
Magnet volume	83.5 $10^{-3} m^3$
Slot width (τ_s, tooth pitch)	0.5 τ_s
Slot width opening	0.25 τ_s
Slot-closing thickness	0.005 m
Slot depth	0.065 m
Active copper volume V_{cu}	95.6 $10^{-3} m^3$
Linear load A	6.17 10^4 A/m
Current density j_s	3.65 10^6 A/m^2

per volumes remain invariant. To convert the three-phase machine into a five-phase one, only the numbers of slots and poles are changed to make a five-phase winding feasible.

3.1 Initial machine analysis

The initial machine has 216 slots and 60 poles. Therefore the number of slots per phase and pole for this 3-phase winding is $s_{pp} = 6/5$. Each pole is made of a fully pitched radial magnet with a 1.17 T remanent magnetic flux density. The pole-slot arrangement yields a fractional-slot winding, which provides an efficient mean of reducing the cogging torque [11]. The fundamental winding factor is 0.927. This three-phase machine is wye-coupled. Therefore the third back-emf harmonic can not be used to produce additionnal torque. According to 2D numerical prediction, the time constant of the elementary machine is about 0.112 s. Considering this value and the nominal speed of 105 rpm, a PWM frequency of 1000 Hz ensures a low level of parasitic current for the entire speed range [12].

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3.2 Five-phase winding requirements

To convert the three-phase machine into a more efficient five-phase one, it is necessary to find a new fractional slot winding that fulfills the following conditions:

- relation (3) regarding the average torque must be verified (condition C1)
- the time constants of both elementary machines must be compatible with the PWM frequency of 1000 Hz (condition C2)
- the third harmonic winding factor must be as high as possible in order to enable the M2 machine to provide a significant torque (condition C3)
- the cogging torque should not be increased when using the new pole-slot configuration (condition C4).

The new slot number must be a multiple of the phase number and the new pole number must remain near enough to the initial value of 60 in order to roughly maintain the same current frequency. It is possible to obtain a five-phase winding with 60 poles and 200 slots but this configuration clearly does not fulfill the condition C4 regarding the cogging torque. Indeed, according to [11], with this configuration, the first flux density harmonic contribution becomes the 5th whereas it is the 9th with the initial three-phase winding. This solution is thus rejected.

3.3 Method used to study the winding

To take full advantage of the opportunity offered by the Permanent Magnet synchronous machines, fractional slot windings which have already been

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studied for three-phase machines [13], are again considered for fault tolerant [14] and multi-phase machines [8]. In this paper, the procedure to determine a convenient 5-phase winding is deduced from [15]. If the phase number, the pole number and the phase number are known, it is possible to deduce a set of coils per phase that leads to balanced multi-phase windings. The procedure is divided into four steps. The first step involves initializing the procedure: it consists of selecting a set of coils per phase that will be examined. The number of selected coils is $N_s/(2N)$ because only single layer windings are explored. The following step verifies that the selected coils yields a feasible winding. The third step concerns the condition C2 regarding the time constants of the 2-phase elementary machines that must be of the same order. The fourth step takes into account the winding factor requirements (condition C3). For each step, if the criteria is not satisfied, the coils selection is rejected and a new selection is examined. Fulfilment of conditions C1 and C4 directly depends on the choice of the pole and slot numbers.

3.4 New five-phase winding

By using the above procedure, it is possible to find a convenient five-phase winding with 180 slots if the pole number is decreased to 58. Each phase is made up of 18 coils. In figure 2, phase 1 winding is represented. The number of slots per phase and per pole for this 5-phase winding is $s_{pp} = 18/29$. The phase 2 winding is shifted 36 slots forward with the phase 1 winding.

In order to determine the electrical quantities, two tools are available: an analytical 2D field calculation software program based on [16] and the numerical 2D software *Difimedi* [17]. Both of these have been successively used. For example, figure 3 shows the magnetic flux distribution when one

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phase is supplied with a constant current obtained with the numerical 2D software. Thus the inductances values and the back-EMF are first analytically estimated and then controlled using the numerical software. The stator resistances are calculated by considering the conductor section and the length for average temperature. The electrical time constant can thus be estimated. All the conditions are fulfilled for this machine.

As shown in figure 4 which compares the two elementary back-emfs for a conductor, condition C1 is verified:

$$\frac{\epsilon_{cd}^{RMS}(5)}{\epsilon_{cd}^{RMS}(3)} = 1.054$$

Consequently the five-phase machine enables us to provide a better average torque than the three-phase one when using sinusoidal supply.

Furthermore, condition C2 is also fulfilled:

$$\tau_1 = 0.152 \text{ s} \quad \text{and} \quad \tau_2 = 0.106 \text{ s}$$

These values are both obtained by 2D analytical and numerical calculations. The difference is about 5% higher for τ_1 and 9% higher for τ_2 with the analytical software. The PWM frequency of 1000 Hz thus remains sufficient to ensure low parasitic currents.

Condition C3 regarding the winding factors is also satisfied: the fundamental winding factor rises from 0.927 to 0.984 while the third harmonic one is equal to the satisfactory value of 0.859, which makes the torque produced by the M2 elementary machine valuable (if the flux density produced by the rotor contains a significant part of the third harmonic).

Finally, concerning condition C4, this new pole-slot configuration guarantees a negligible cogging torque since the first flux density harmonic con-

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tribution is the 45th. As underlined in the previous section which introduced the multimachine design, the multiphase topology enables a better use of the magnet volume. This aspect is illustrated in the second section which deals with the issue of magnet layer optimisation.

4 Magnet layer optimisation

For given geometrical dimensions (stator diameter, mechanical airgap, magnet layer thickness and slot parameters), the back-emf depends on two design elements: on the one hand, the winding studied in the previous section; on the other hand, the rotor geometry examined in this section. This section looks at magnet layer adaptation to the multimachine supply strategy in order to improve the torque density.

4.1 Multimachine design requirements regarding magnet layer

With regards to the windings, the ideal rotor structure is the one that only generates the first harmonic of each 2-phase elementary machine (first harmonic for M1 and third one for M2). In this way, each elementary machine has a sinusoidal back-emf and can provide a constant torque in the case of multimachine supply (as explained previously in 2.2). For the given five-phase machine, it is interesting to look for a particular magnet layer that favours first and third harmonics in the back-emf spectrum. Furthermore, according to the sinusoidal back-emf objectives for the two elementary machines, the other back-emf harmonics that belong to the two harmonic families (see figure 1) must be as weak as possible: the torque ripples are equal to zero if these conditions are fulfilled. In practise, for the M1 elementary machine, harmonic 1 (the fundamental) must be high and harmonics 9 and 11 low; for the M2 machine, harmonic 3 must be high and harmonics 7 and

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13 low. For the given machine, owing to the large airgap effect that reduces high order flux density harmonic and the corresponding winding factors that filter harmonics 7, 9, 11 and 13, this constraint is naturally respected.

4.2 Problem analysis

For the given machine, as the winding is chosen, the only way to act on the back-emf spectrum is to modify the no load airgap flux density waveform. The objective is to increase the first and third harmonics in comparison with respect to initial propeller configuration where the pole consists of a fully pole pitched radial magnet. It should be noticed that such a pole configuration allows us to obtain a higher value for the airgap flux density than the one obtained with the more classical configuration where the magnet arc to pole pitch ratio is about 2/3. This second configuration is not convenient in this instance because the back-emf third harmonic that is required by the M2 elementary machine to produce torque is null. The fully pole pitched configuration is thus more interesting since the no load airgap flux density contains both first and third harmonics. Unfortunately this improvement comes with an increase in the interpolar flux density leakage. For the machines with high airgap to pole pitch ratios, the fully pole pitched radial magnet configration leads to important interpolar leakage flux, which can be considered as an inefficient use of the magnet volume.

The approach proposed in this section is to change the pole magnet layer characteristics in order to obtain a more convenient airgap flux density than the one corresponding to the initial magnet layer (fully pole pitched). The optimised magnet layers must provide an airgap flux density spectrum with higher 1st and 3rd harmonics than in the initial case. Reaching this goal is equivalent to reducing the interpolar flux density leakage, leading to better

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use of the magnet volume.

4.3 Method

It is decided to look for a pole composed of three magnets with parallel magnetisation. All the magnets have the same magnetisation value. This approach is comparable to the segmented Halbach array path, so called flux focussing technology [18]. Due to the hypothesis of pole symmetry, the introduction of two design parameters is sufficient to formulate the optimisation variable:

- the length of the adjacent magnet L can vary from 0 $^\circ$ to 90 $^\circ$ (electrical degrees)
- the orientation angle γ of the magnetisation of the adjacent magnet can vary from -90 $^\circ$ to 0 $^\circ$

These two parameters define the optimisation variable $x = (L, \gamma)$. They are depicted in figure 5. By using a rather precise analytical flux density calculation [16], the flux density spectrum for the five-phase machine with poles made of fully pitched radial magnets can be estimated (and controlled with the numerical calculation tool *Difimedi*). The 1st and 3rd harmonic amplitudes take the following values:

$$B_1^{ref} = 1.04 \text{ T} \quad \text{and} \quad B_3^{ref} = 0.52 \text{ T}$$

The optimised magnet layer must improve on these two values. The solution x must thus satisfy the following condition:

$$\frac{B_1(x)}{B_1^{ref}} \geq 1 \quad \text{and} \quad \frac{B_3(x)}{B_3^{ref}} \geq 1 \tag{4}$$

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The speed and the sufficient accuracy of the analytical calculation method make the estimation of these two ratios possible for numerous values of x. The results are presented by the figure 6. The best improvements for the fundamental and the third harmonic are respectively about 5.9% and 28.5%. As these maximal values are not reached for the same point x, a compromise must be realized: it consists in choosing the point x that leads to the better average torque with the multimachine supply strategy. By taking into account the winding factors and the slot parameters, the fundamental and third-harmonic back-emf can be estimated, which allows the prediction of the EM torque. So it can be shown that the better point is:

$$x_{opt} = (0.29\,\pi_{elec}/2, -47\,deg) \Longrightarrow \begin{cases} \frac{B_1(x_{opt})}{B_1^{ref}} = 1.056 \\ \frac{B_3(x_{opt})}{B_3^{ref}} = 1.238 \end{cases}$$

The figure 6 also shows the point x_{hal} that corresponds to the Halbach array solution (the Halbach array with three magnets per pole). This solution is less interesting because the third harmonic is significantly lower (1.196 for x_{hal} againt 1.238 for x_{opt}) whereas the fundamental has the same level (1.057 for x_{hal} against 1.056 for x_{opt}). It can be noticed that, as an Halbach Array, the chosen topology partially focuses the PM magnetic flux in the magnet layer. So, with this configuration, the back iron core thickness can be reduced from $30mm$ to $18mm$ according to the numerical software *Difimedi*.

4.4 Results

Concerning the back-emf waveform, the figure 7 compares the elementary machines back-emf for the radial magnet five-phase machine with the optimised ones (for the same active volume). The analytical results, confirmed by the 2D numerical ones, are really satisfying: the amplitudes are higher

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Table 2: Analytical results concerning the torque improvement

Machine	Magnet layer	Supply	Avg torque	Torque ripples
3-phase	Conventional	sinus	T_0	t_0
3-phase	Optimised	sinus	$1.06\,T_0$	$0.95\,t_0$
5-phase	Conventional	sinus	$1.05\,T_0$	$0.64\,t_0$
5-phase	Optimised	sinus	$1.11\,T_0$	$0.02\,t_0$
5-phase	Optimised	1 & 3	$1.15\,T_0$	$0.29\,t_0$

and the signals are more sinusoidal. The back-emf first harmonic is increased by 5.5% and the third harmonic back-emf by 23%. In comparison with the initial three-phase machine, the fundamental improvement is more than 11.2%. Obviously this comparison is more pertinent if the magnet layer optimisation method is also used for the three-phase machine. In this case (where the optimal point is $x = (0.43\,\pi_{elec}/2, -39\,deg)$), the results remain convincing: the increase is about 4.8% (mainly due to the better fundamental winding factor of the five-phase machine).

The wye coupled three-phase machine however can not use the back-emf third harmonic to provide torque. This explains why the EM torque provided by the five-phase machine with the optimised magnet layer is always higher than the one produced by the three-phase machine even if its magnet layer is also optimised. This assertion is illustrated by figure 8, which represents the EM torque produced by the different machine configurations. The reduction of the pulsating torques for the five-phase machine is quite clear. The results, according to analytical predictions, are summarized in table 2 which provides values for the average torque and the torque ripples (maximum minus minimum) with respect to the initial three-phase machine where $T_0 = 191\,kNm$ and $v_0 = 2.13\,kNm$. It can be noticed that, for the optimised magnet layer five-phase machine, the sinusoidal supply is sufficient to obtain an improved EM torque with regards to the amplitude and

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ripples. Concerning this point, it is logical to obtain additionnal ripples when the M2 machine is supplied to produce torque: the phenomenon results from the harmonic interaction between the third harmonic current and the back-emf harmonics that belong to the corresponding harmonic familly (7, 13, ...). However the level of ripples remains low in comparison with the initial value.

5 Conclusion

Given that the multimachine approach provides a synthetic view of the multiphase machines in terms of both control and design, it is possible to consider the number of phases as a design parameter of a drive. Specific example of an application of this principle has been given in this paper related to a marine propeller where the torque density and the torque ripples are of critical importance and the fault tolerance appreciated. Design objectives for the electrical time constants and the emf spectrum have been identified. The choice of an adapted fractional slot five-phase winding and the optimisation of the magnet layer characteristics significantly improve the torque quality, in comparison with the initial three-phase configuration, and increase the fault tolerance. Particularly, the five-phase topology allows better use of the magnet volume. Of course, this advantage for the machine could be tempered by the apparent need for a higher number of switching devices. In fact, this must be carefully studied because, for high power, a switch is often a combination, in series and/or parallel, of elementary semiconductor devices. In this case, the tolerance to semiconductor device breakdown appears to be more even advantageous with multiphase machines.

Despite the promising nature of the results, two main drawbacks must

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be considered. First, the simulations used in this paper are based on 2D field calculations, which means that end-turn effects are not taken into account. The mutual phase fluxes related to the end-turns and the estimation of the required copper length are not carried out. However the pulsating torque reduction is guaranteed. The other moderating argument concerns the magnetomotive force distribution generated by the new five-phase winding. As the MMF subharmonics can induce mechanical stresses [19], it would be useful to assess their influence. To summarize, the expected benefits of the five-phase topology need to be more accurately estimated.

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6 Figures

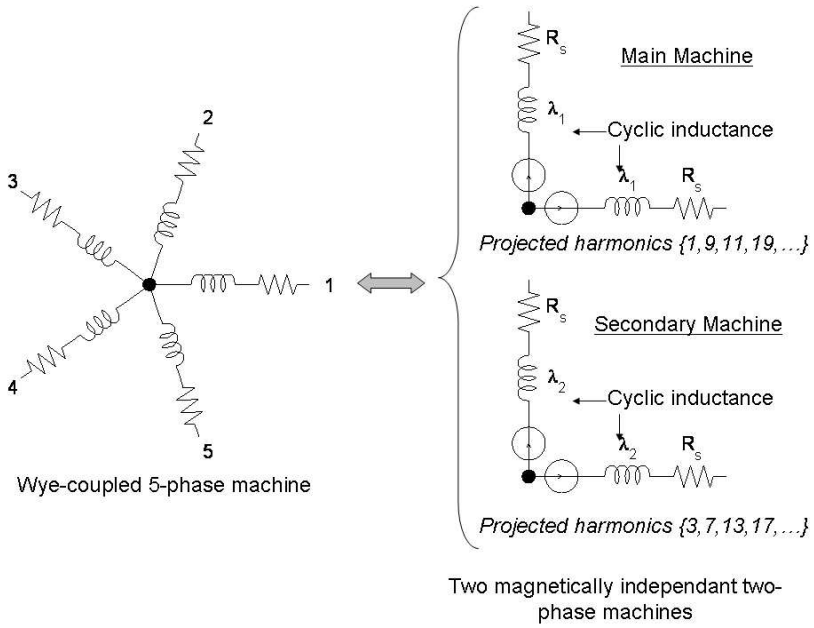

Figure 1: Multimachine decomposition for a wye-coupled 5-phase machine

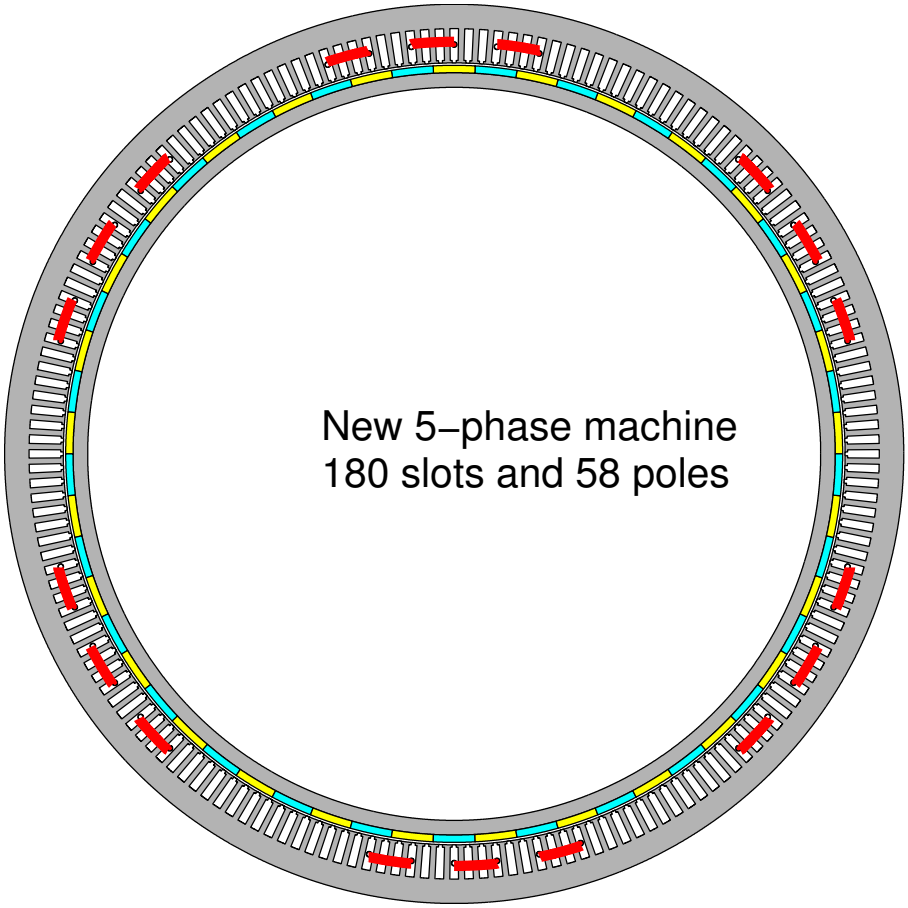

Figure 2: Winding configuration of a phase for the 5-phase machine

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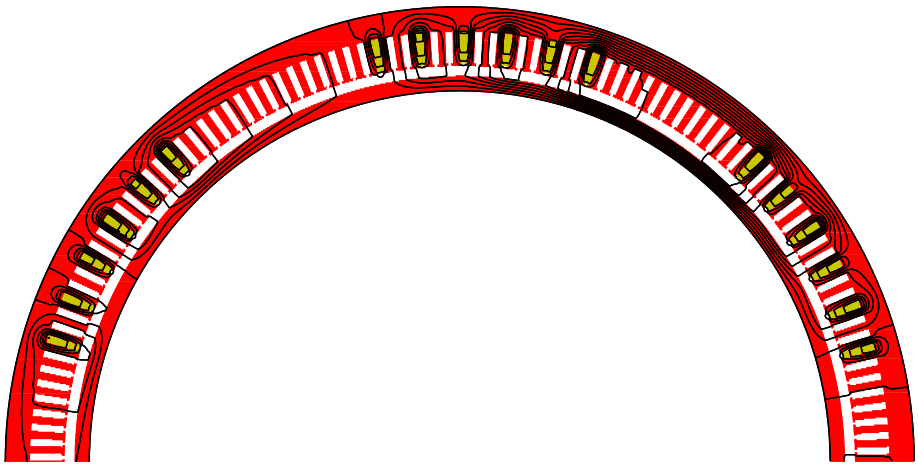

Figure 3: Magnetic flux distribution when one phase is supplied with a constant current (new machine) according to the numerical 2D software

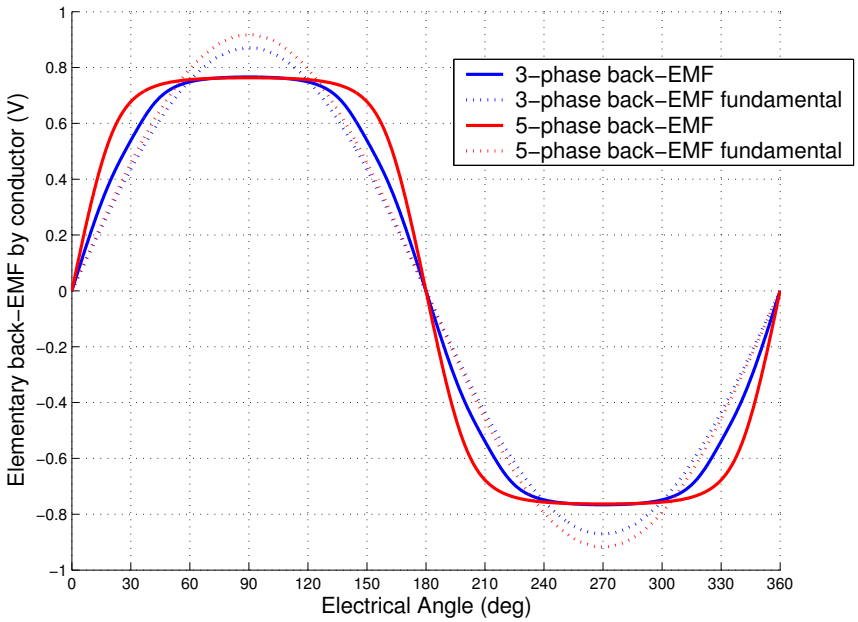

Figure 4: Comparison of the elementary back-EMF by conductor $\epsilon_{cd}(3)$ and $\epsilon_{cd}(5)$ (analytical estimations)

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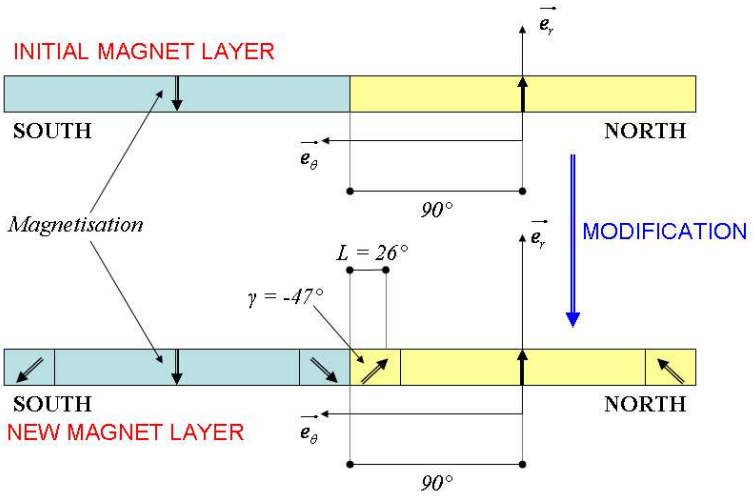
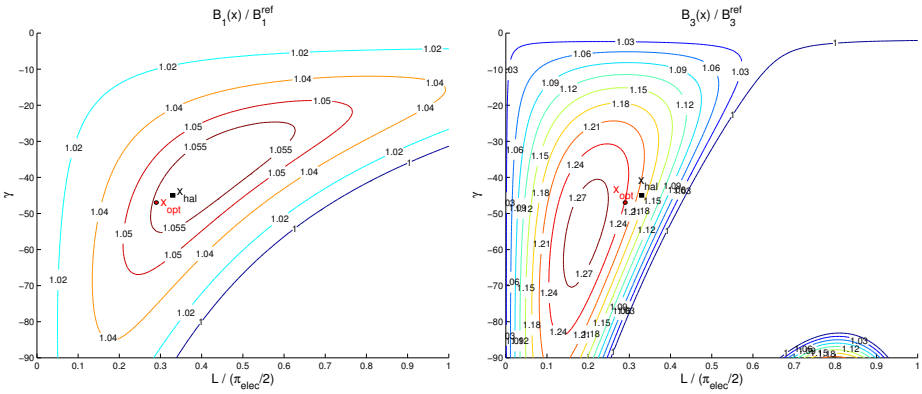


Figure 5: Modification of the magnet layer



(a) Fundamental flux density change (b) Third harmonic flux density change

Figure 6: Flux density change with optimisation variable (L, γ)

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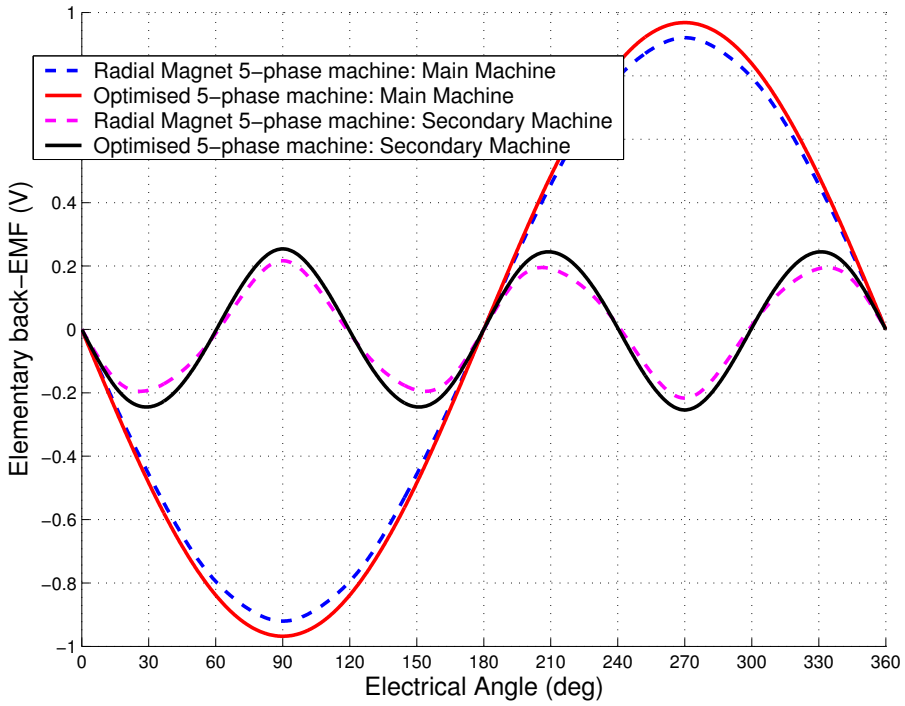

Figure 7: Elementary machine back-EMF improvement (analytical estimation)

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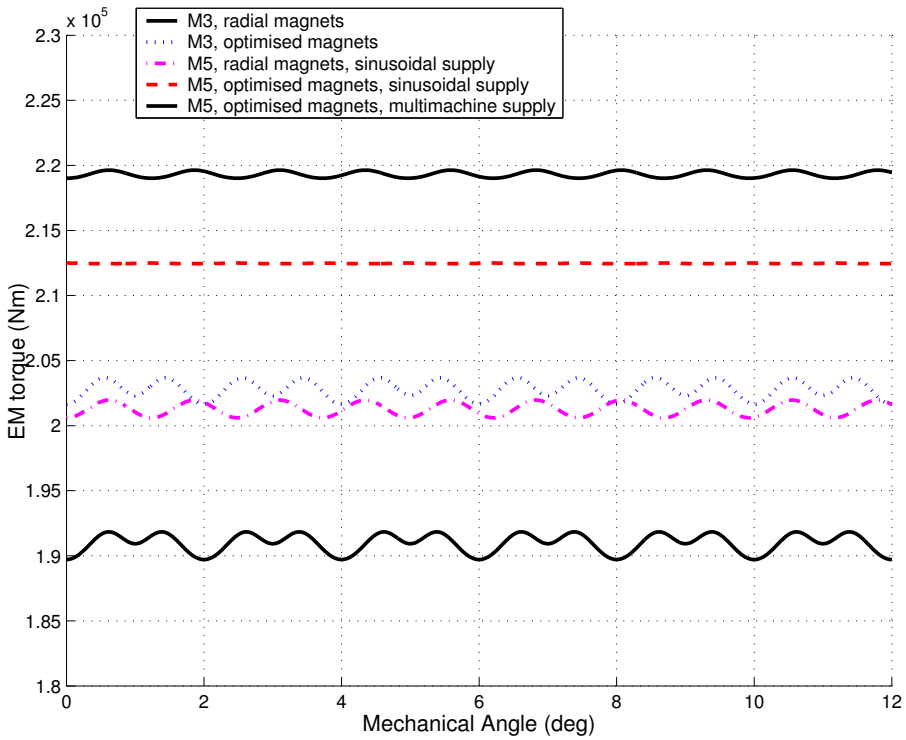

Figure 8: EM torques comparison for the 3-phase and 5-phase machines with conventional and unconventional magnets layer

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