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Two-Slot Coil Pitch For Five-Phase Integrated Permanent Magnet Synchronous Machine

R. Cousseau and R. Romary, *Member, IEEE*, R. Pusca and E. Semail

Abstract—This paper presents a simple method to size a concentrated winding permanent magnet synchronous machine when a high number of slots is needed. A classical concentrated winding machine leads to a number of pole pairs close to the number of slots to be efficient. Thanks to a two slots pitches winding, number of slots can be doubled without deteriorate the winding factor. Moreover, this specific winding is also useful to deal with embarrassing magnetomotive force harmonics. The method is detailed here for a specific case of a machine with integrated power converter. Sizing of the machine is also presented and finite element simulations results show performances of this design compared to a conventional one.

Index Terms—permanent magnet synchronous machine, concentrated windings, two slot coil pitch, design, multiphase machine

I. INTRODUCTION

Permanent magnet synchronous machines (PMSM) are widely used as electrical machine in a large kind of applications. They are able to provide high torque/mass ratio with a very good efficiency due to the absence of DC rotor currents [1]–[5]. At the stator, concentrated windings can be interesting to combine with a permanent magnet rotor and the one slot pitch winding is nowadays the most popular one [6]–[8]. This kind of winding has many advantages. First, it is very simple to realize as each coil can be mounted or replaced independently of the other coils. Then, this kind of winding generates less joule losses due to the short end winding parts at the front ends of the machine. Moreover, concentrated windings enables many winding configurations which makes possible the design of multiphase machines with a convenient arrangement of each coil. Compared to three-phase machines, multiphase machines are interesting because they allow to divide the power converter in more than three parts with smaller electronic components. Moreover, it is possible to keep driving the machine in case of one or more faulty phases using a convenient fault tolerant control [9]–[16].

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This increases the reliability of the machine. Concentrated winding leads to a fractional pole pitch that can bring many drawbacks. Actually, depending on the number of pole (p), the number of slot (N_s) and the number of phase, the most convenient winding arrangement does not lead necessarily to a good winding factor [17], [18]. Winding factor close to 1 is obtained when the number of slots and the number of poles differ from 2 [19]. The aim of this paper is to design a 45kW, 5-phase permanent magnet synchronous machine with concentrated winding where the power converter is integrated. The idea is to place two power converters in the flange at the front end of the machine. Each converter supplies half of the phases which are split in two parts. By this way, it is possible to obtain a double 5-phase machine with enhanced reliability because the supply power is shared between two converters. For mastering the integration of one converter at each axial ends of the machine, the number of connections between the coils of each phase and the end-windings must be reduced as much as possible. Tooth concentrated windings are quite attractive but for a given number of poles, requirement to get a high winding factor leads to a small number of teeth for practical implementation. A two-slot coil pitch with small overlapping appears to be a good compromise [20]–[25]. [20] shows that this kind of winding make possible to obtain the power factor of a N_s -slot/ $2p$ -poles machine with a $2N_s$ -slot/ $2p$ -poles machine. The paper is organized as follows: section II deals with the design of the winding of a 40/18 (40 slots, 18 poles) machine having a similar winding factor (almost 1) than a 20/18 one. Section III gives the sizing of a 45kW machine with double slot pitch concentrated winding. Section IV highlights the performances of the machine through a 2D finite element simulation. Finally, a conclusion is given in section V.

II. DESIGN OF 2 SLOT PITCH WINDING MACHINE

As previously said, the present study is about a 5-phase machine. The slot/pole combinations known to be the most efficient regarding winding factor and torque maximization are $N_s = 2p \pm 1$ or $2p \pm 2$. Thanks to that, the 20/18 combination should be very interesting. However, this case presents very embarrassing magnetomotive force (MMF) harmonics while the winding factor is close to 1. A solution is to double the number of slots without changing the number of poles but the 40/18 combination gets a very low winding factor. In order to keep a high winding factor and remove the MMF harmonics issue, a 2 slot pitches winding can be used as it is explained below.



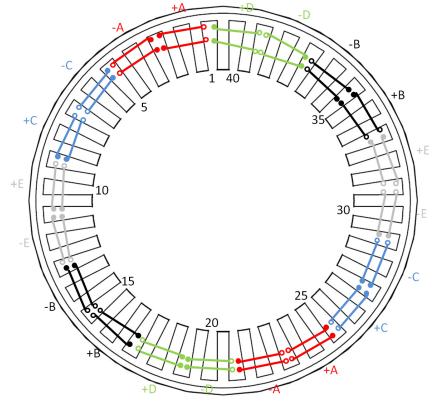
Fig. 1: Optimal winding sequence for a 5-phase 20/18 combination

A. Two slot pitch winding method

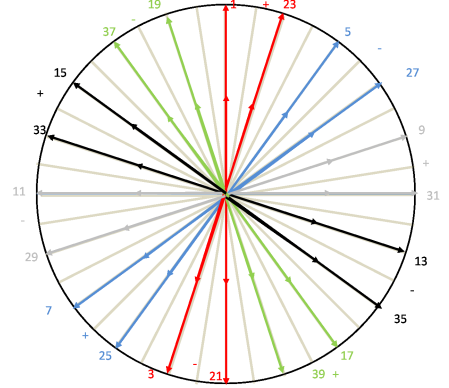
At first, the optimal winding of the reference machine (20/18) must be found. According to a specific method [26], the best winding sequence is describe in Fig. 1. The next step is to represent this winding in a 40 slots machine but only considering half of the teeth as shown in Fig. 2a. It can also be seen that each winding has been doubled. Indeed, the 2 slot pitch winding technique is achieved by rotating the inner coils from the outer ones. Another representation named star plot representation can be useful to know how to modify the windings. It is made of vectors that correspond electrically to all the coils in a slot. For example, the phase A starts positively from the slot number 1 and negatively from the slot number 3. So, as the electrical angle between 2 slots is equal to 81° for a 40/18 combination ($\alpha = 360 * 9/40$), these 2 vectors are separated by 162° as shown in Fig. 2b. By repeating this for each slot, the entire star plot configuration is obtained. Every vector has been doubled in order to consider the outer and inner winding circle. At this point, vectors corresponding to the inner circle are rotated and are affected to the even slots (Fig. 2c). For example, the slot electrically separated from the number 1 by 351° is the number 32. Therefore, as it is next to a positive vector, it is also considered to be positive. This means that the winding from the slot 32 to 34 will be in the inner circle and positive. The idea is to keep vectors of a same phase together, this explains why vectors 32, 14, 34 and 12 are affected to the phase A. Finally, the entire two slot pitch winding for 40-slots/18-poles combination is shown in Fig. 2d .

B. Comparison of winding factors and MMF harmonics for these configurations

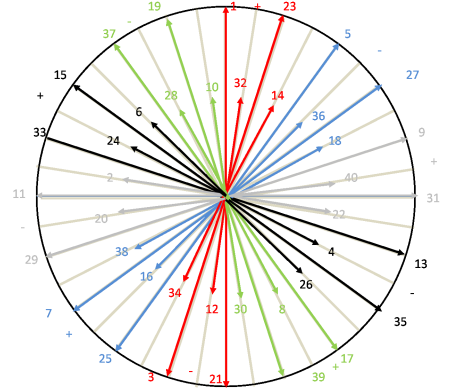
The method to achieve a two slot pitch winding has been explained but the winding factor has to be determined. Indeed, using a method described in [27], the winding factor can be calculated with the star plot representation as well. Results are presented in Table I. Even if the winding sequence of the 40/18 one slot configuration has not been presented, it can be obtained with same technique as the 20/18 one. Winding factor values are very close to 1 as expected for the two first configurations. The winding factor for a "classical" 40/18 with single pitch winding is also calculated. As said before, this one is very low and not sufficient enough for the design of high power density machine. Finally, MMF harmonics have to be evaluated. Fig. 3 presents stator MMF harmonics per unit value for the three configurations. The principal harmonic for every case is the ninth and is equal to the number of pole pairs. It can also be observed that the 20/18 machine presents an embarrassing harmonic very close



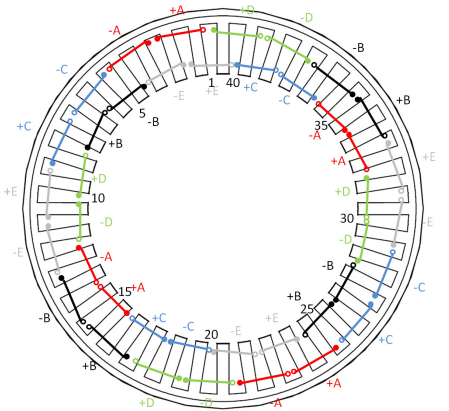
(a) 5-phase 20/18 combination in a 40 slots machine



(b) Star plot of a 20/18 winding in a 40 slots machine



(c) Star plot of 40/18 machine with two slot pitches



(d) Two slot pitches winding for a 40/18 machine

Fig. 2: Steps of the two slot pitches winding method

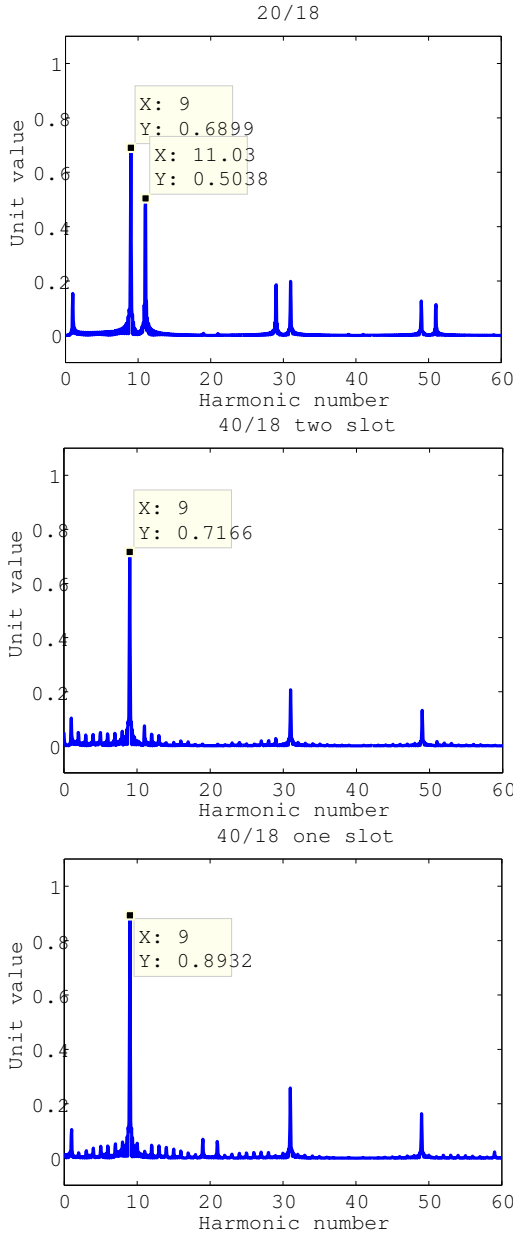


Fig. 3: MMF Harmonics for the three configurations

to the principal one. This harmonic will produce additional losses in the rotor iron and in the magnets. On the contrary, both 40/18 configurations do not have this problem. On conclusion, the two slot pitch winding method has been presented with the purpose to double the number of slots of a 5-phase machine. Results concerning winding factor and MMF harmonics have been shown. These results prove the benefits of such method for this particular case.

TABLE I: Winding factor for different configurations

	20/18	40/18 two slot	40/18 one slot
Winding factor	0.9755	0.9725	0.65

III. SIZING OF A TWO SLOT PITCH SYNCHRONOUS MACHINE

The aim is to design a 5-phase, 45kW permanent magnet synchronous machine with concentrated two slot pitch stator winding. The rated torque of the machine is 100 Nm that have to be delivered up to 4500rpm. The machine has 40-slots/18-poles, it is supplied by two power converters placed in the flanges (Fig. 4), energized by a 300V DC bus. Each converter supplies half of the 5-phase stator winding. For the sizing of the machine, a usual approach based on an analytical model of the machine will be used. This approach is generally associated with a 2D or 3D Finite Element Analysis (FEA) that allows to check if the specifications of the machine are reached. The FEA also enables to adjust some design parameters of the analytical model that can be processed again to adjust the sizing. For example, the magnitude of the airgap flux density B is an input parameter of the analytical model, but only the FEA can provide its value accurately. The iron losses in the machine can also be computed with the FEA. The analytical model also requires to impose two other parameters: A , the linear current density along the airgap, and J the surface current density in the winding. The value of A and J have to be chosen in accordance with the cooling process of the machine, but without thermal analysis, it is advised to take typical values depending on the power and the size of the machine [28]. The initial formula for sizing a machine is described in (1) :

$$D^2 L = \frac{2C}{BAK} \quad (1)$$

C is the rated torque, D is the rotor diameter, L is the machine length. $D^2 L$ is proportional to the volume of the rotor. K is the winding factor. The volume of the machine is decreased when this value is high (close to 1). For the sizing of the stator, the surface current density J will directly impose to size of the stator slots, verifying the magnetic constraints (saturation) of the teeth and the yoke. By taking $A=27000$ A/m, $J=5$ A/mm², $B=1.25$ T, and $K=0.97$, geometrical parameters are obtained. Table II gives the main dimensions of both machine. Thanks to a higher winding factor K , the rotor volume is reduced in the case of the two slot pitch machine (approximately about 33%). It should be noticed that the proposed design does not take into account the real coil surface in a slot. Indeed, because of this specific winding, half of the surface of each slot is unused. So, it could be necessary to increase slot size and so the stator outer diameter. A more realistic design would not lead to such a small machine. Another disadvantage of the two slot pitch winding is the longer end winding parts compared to a one slot pitch machine. This results in higher joule losses. Concerning to stator winding, the coils of each half-phase are series connected. Therefore, in order to fulfill the 300V DC voltage supply, each coil has 16 turns.

IV. SIMULATION RESULTS

Finite-element simulations have been carried out to quantify performances of the designed machine. The purpose of

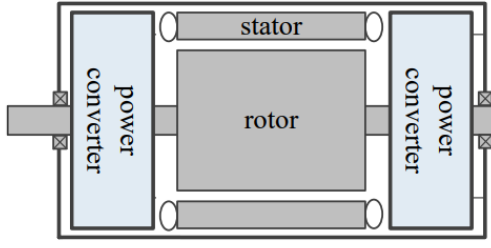


Fig. 4: Integrated, two converters synchronous machine

TABLE II: Geometrical parameters of the machine

Configuration	One slot pitch	Two slots pitch
Length of the machine	150 mm	150 mm
Rotor diameter	150 mm	122 mm
Airgap	1mm	1 mm
Stator outer diameter	227 mm	197 mm
Slot depth	32.6 mm	32.6 mm
Slot pitch	11.94 mm	9.74 mm
Magnet thickness	3.98 mm	4.7 mm

these simulations is to compare a "classical" 40/18 machine with single pitch winding and the new one. Fig. 5 shows the global structure of the two slot pitch machine and can be compared to the one slot pitch configuration (Fig. 6). It is smaller than the one slot pitch machine especially regarding rotor diameter. The other difference is obviously about the winding. Simulations are made during one electric period while the rotor speed is constant (4500 rpm). First, no load is applied to the machines in order to analyze back-EMF as shown in Fig. 7. Spectrum of these back-EMF (Fig. 8) presents a higher main harmonic for the two slots machine whereas the total number of turns are the same. This is due to the higher winding factor compared to the one slot pitch machine. Moreover, the third harmonic is reduced.

In load conditions, currents are imposed at the same

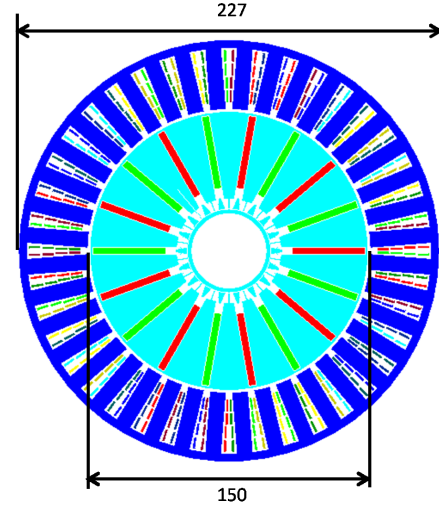


Fig. 6: Structure of the one slot pitch machine

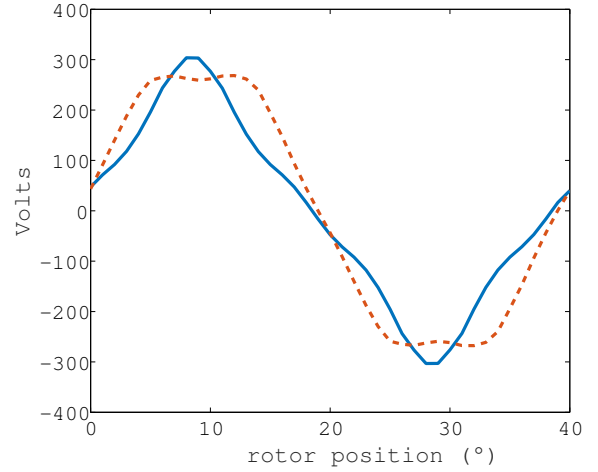


Fig. 7: Back-EMF

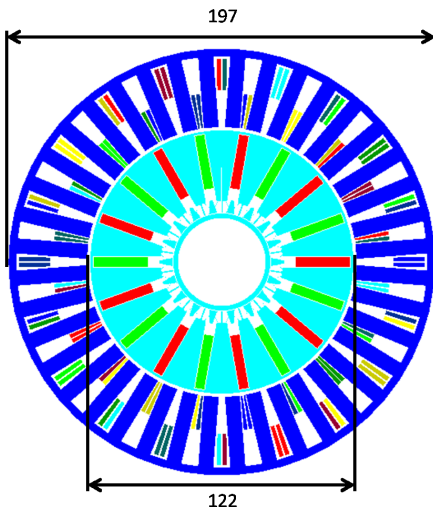


Fig. 5: Structure of the designed machine with two slots pitch

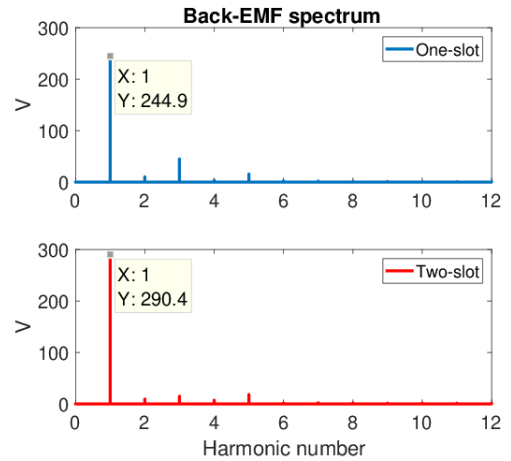


Fig. 8: Back-EMF spectrum

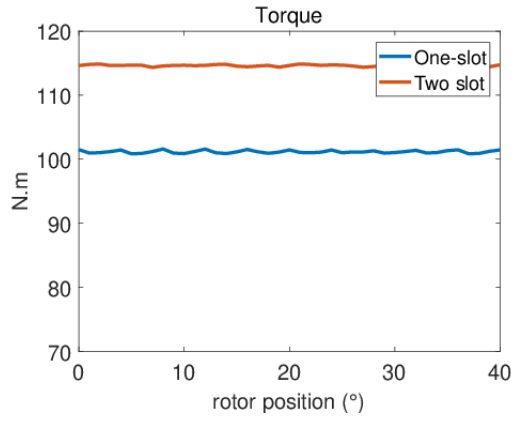


Fig. 9: Torque comparison at nominal point

value of approximatively 28 A RMS for each case and are purely sinusoidal at a frequency of 675 Hz. A classical vector control is ensured with the currents put in phase with back-EMF. Fig. 9 shows the calculated magnetic torque. Value for new configuration is equivalent to the other one and even greater whereas dimensions are smaller. This can be explained because of the real induction values. Indeed, airgap flux density B is an entry parameter for dimension estimation but is different in the FEA and our case higher for the two slots pitch machine. Torque ripple is also slightly reduced. Moreover, according to Table III, iron losses are considerably reduced which is mainly due to the size reduction.

TABLE III: Iron losses comparison at nominal point

	One slot	Two slots
Iron losses (kW)	2.5	1.5

V. CONCLUSION

This paper has presented an efficient way to design a permanent magnet synchronous machine when a high number of slots is required. A multiphase machine with integrated converters has been introduced. The two slot pitches winding method has been explained. Thanks to this, it is possible to obtain a good winding factor while the number of slots is very different from the number of poles. Moreover, it has been shown that there is no embarrassing magnetomotive force harmonics in this configuration. Sizing has been carried out as explained according to usual equations. Finally, thanks to finite element simulations, performances of the machine have been verified. Results are very promising because torque is higher than expected and moreover, iron losses are reduced compared to an identical machine with a classical winding.

VI. ACKNOWLEDGMENT

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