Guidelines for Designing Concentrated Winding Fractional Slot Permanent Magnet Machines

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Abstract-**The paper discusses the guidelines for designing concentrated winding fractional slot permanent magnet machines. The winding factor and different slot and pole combinations are studied. Various low-speed high-torque permanent magnet synchronous motors with concentrated windings and with different slot and pole combinations are calculated analytically and by applying the finite element method (Flux2D™ by Cedrat). All the motors calculated in this study have the same frame size, air-gap diameter, air-gap length and the same amount of permanent magnet material.**

***Index Terms*—permanent magnet machines, concentrated windings.**

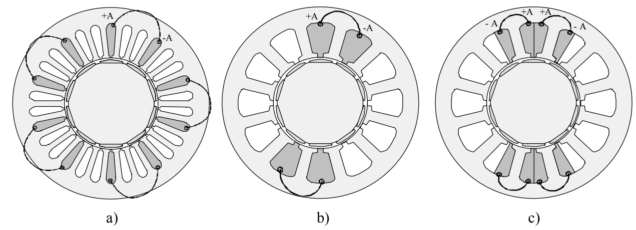

Fig. 1. End windings of one phase of 10-pole machines: a) a traditional one-layer winding with $Q_s = 30$ and $q = 1$, b) a one-layer fractional winding $Q_s = 12$ and $q = 0.4$ and c) a two-layer fractional slot winding with $Q_s = 12$ and $q = 0.4$, where the slot is divided vertically [1].

I. INTRODUCTION

The winding is called a fractional slot winding, if the number of slots per pole and per phase is not an integer number

$$q = \frac{Q_s}{2pm}. \quad (1)$$

Q_s is the number of stator slots, p is the rotor pole pair number and m is the number of stator phases. When each coil is wound around one tooth, the winding is called a concentrated winding. Such a permanent magnet machine may be used in low-speed applications, in which stator copper losses are dominating and iron losses are less important. In cases where the frequency of the stator is less than or equal to 100 Hz, the iron losses – depending on the stator core material – are typically not as significant as copper losses. The fractional slot PM synchronous machine produces some losses in the rotor and it is therefore inherently best suited for low speed applications.

In the study, a high torque production capacity and a good torque quality are searched; such PM motors are considered in which the permanent magnets are located on the rotor surface and the stator slots are semi-closed or open. Figure 1 illustrates the end windings of a traditional permanent magnet machine and the corresponding end windings of a concentrated fractional slot permanent magnet machine.

It is easy to see that the end windings of the fractional slot concentrated windings ($q \leq ½$) are notably shorter than the end windings of integral slot windings. The insulation and manufacturing systems are also easier in the fractional slot windings since the end windings are not overlapping each other. The winding width may, however, be far less than the pole pitch in these machines, which causes some inherent ineffectiveness in this machine type. The fractional slot windings may be divided into one-layer windings, Fig. 1 b) or two-layer windings, Fig. 1 c). In a two-layer winding, a slot is divided into two different parts, in which the coil sides may belong to different phases.

II. WINDING FACTOR

In principle, a machine should have a large fundamental winding factor. The winding factor is usually proportional to the electromagnetic torque generated. Machines with a low fundamental winding factor use the winding turns ineffectively and also usually have a low pull-out torque. To compensate this, a high current or more winding turns have to be used, and consequently, the stator leakage inductance may start to dominate the machine behaviour. The fundamental winding factors for some concentrated windings for different rotor pole and stator slot combinations are given in Table I.

The fundamental winding factors vary remarkably and the highest possible values seem to belong to the arrangements that produce unwanted unbalanced magnetic pull. These machines might work well in applications where the stator slot and rotor pole numbers could be doubled or tripled. For instance, instead of a 9/8-machine, 18/16 or 27/24 machine could be used without major mechanical problems. It seems that the designer has to be satisfied with winding factors such as 0.933 for the 12/10 machine or 0.866 for the 12/8 machine. It is shown later

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TABLE I
WINDING FACTORS FOR TWO LAYER CONCENTRATED WINDINGS [6]

Slot number	Pole number 4	6	8	10	12	14	16	20
6	0.866		0.866	0.500		0.500	0.866	0.866
9		0.866	0,945*	0,945*	0.866	0.617	0.328	0.328
12			0.866	0.933		0.933	0.866	
15				0.866		0,951*	0,951*	0.866
18					0.866	0.902	0.945	0.945
21						0.866	0.890	0,953*
24							0.866	0.933
27								0.877
30			q > 0,5					0.866
33								
36								

Slot number	Pole number 22	24	26	28	30	32	34	42
6	0.500		0.500	0.866		0.866	0.500	
9	0.617	0.866	0.949	0.949	0.866	0.617	0.328	0.866
12	0.250		0.25			0.866	0.933	
15	0.621		0.39					
18	0.902	0.866	0.647					
21	0,953*		0.89	0.866				
24	0.949		0.949	0.933		0.866	0.760	
27	0.915	0.945	0.954	0.954	0.945	0.915	0.877	
30	0.874		0.936	0.951		0.951	0.936	
33	0.866		0.903	0.928		0.954	0.945	
36		0.866	0.867	0.902	0.933	0.945	0.953	0.933

*not recommended because of the unbalanced magnetic pull

in this paper that for instance the torque production capability of a 12/8 machine is very good despite its low winding factor.

III. UNWANTED MAGNETIC PULL

A high winding factor does not guarantee good machine properties. A winding produces unwanted unbalanced magnetic pull, when all coil sides of one phase are in the same side of machine. As an example of such a machine, one machine with nine stator slots and eight rotor poles has been calculated for a different power level and speed than the other machines in this paper. The 9-slot-8-pole machine produces 18.5 kW at 3000rpm output power.

The number of poles should not be selected to be almost equal to the number of slots in the case of a concentrated three-phase winding. The machines with an odd number of slots, e.g. 9-slot-8-pole, 21-slot-20-pole and 21-slot-22-pole and also a special case where $Q_s \approx 2p$ (24-slot-26-pole) have been

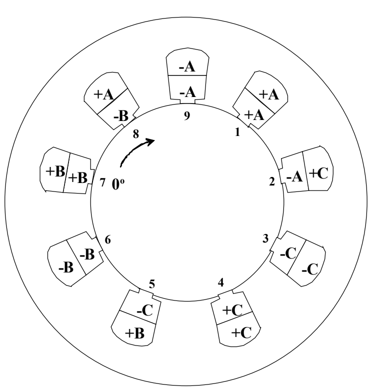

Fig. 2. Winding arrangement principles for the machine with nine slots.

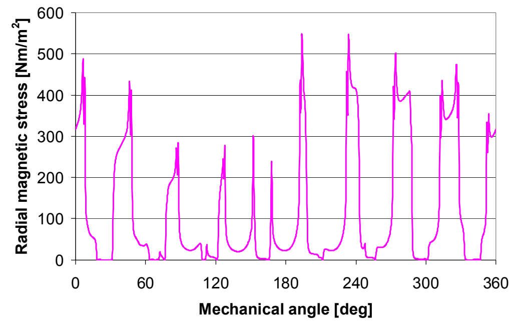

Fig. 3. Radial magnetic stress along the air-gap diameter for 9-slot-8-pole machine (obtained with FEA). t = 0.25 s.

calculated with FEA; all these machines produce an unwanted magnetic pull effect. The effect also causes a very unstable pull-out torque.

Figure 2 shows the winding arrangements for the 9-slot-8-pole machine. The figure shows only the principle of the arrangement, and does not illustrate a real machine. However, it is obvious that all the coil sides of for instance the phase a are on the same side of the machine, and an unbalanced magnetic pull will result. By doubling the number of poles and slots, the unbalance will be cancelled, yet some difficulties may still remain, because the magnetic attractive forces are very unevenly distributed on the stator periphery.

Figure 3 describes the radial magnetic stress along the air-gap perimeter (from finite element analysis, FEA) for the 9-slot-8-pole machine. Figure 3 shows that the pull effect is caused by the radial forces that are notably higher on one side of the machine than on the other side.

IV. PULL-OUT TORQUE

In the following study, all the machines have the same frame size (225), speed, a fixed air-gap diameter and a 45 kW output power at 400 rpm, and also the same amount of magnet material. Fig 4. shows the pull-out torques with different values of q for 24-slot machines. The slot number remains the

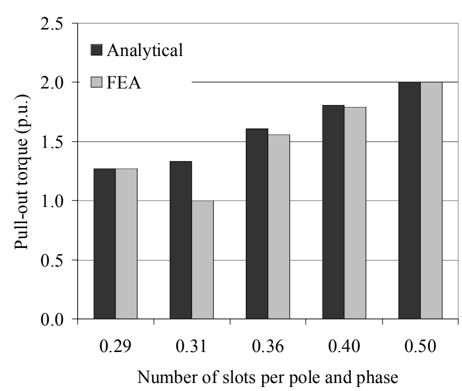

Fig. 4. Pull-out torque with different slot and pole combinations for 24-slot machines.

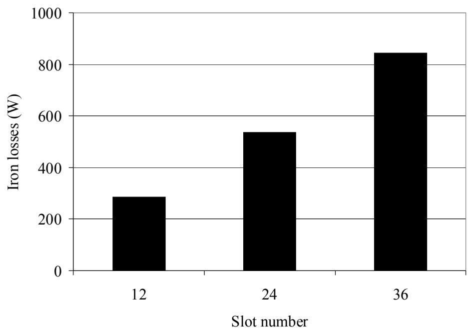

Fig. 5. Iron losses for $q = 0.4$ machines.

same, but the pole number varies. As the number of poles increases, the maximum torque decreases. This may be due to the stray flux of the magnets. When the number of slots is kept constant but the number of poles is increased (while the amount of magnet material is kept the same), the relative amount of the leakage flux increases.

Fig. 5 shows the iron losses for different slot and pole combinations, when $q = 0.4$. A high pole number requires a higher supply frequency, which increases the iron losses.

V. Cogging Torque and Torque Ripple

Cogging is an oscillatory torque caused by the tendency of the rotor to line up with the stator in a particular direction where the permeance of the magnetic circuit from the standpoint of the permanent magnets is maximized. Cogging occurs even when there is no current in the stator. A fractional slot machine may produce a low no-load cogging torque. The cogging frequency is high in these constructions.

When the motor is running, there are also other additional oscillatory torque components because of the interaction of the magnets with the space-harmonics and with the current linkages created by the current harmonics. These additional oscillatory torque components are generally referred to as torque ripple, while the term cogging is often used for the no-current situation [1]–[4].

When a low cogging torque and a low torque ripple are required, the least common multiplier LCM appears to be a useful and also easily available parameter. The number of cogging periods per rotor revolution depends on the least common multiplier LCM of Q_s and $2p$. When both the number of slots and the number of poles are doubled, also the LCM increases [3, 4]. This means that the cogging torque is lower for the machines with multiple poles and slots compared to the simpler structures [4]–[5].

A high LCM number indicates that the value of the torque ripple is small, except in some special cases where $Q_s \approx 2p$, because of the possible unbalanced pull effect. With a low LCM or with q equal to 0.5 or 0.25, it can be expected that the torque ripple is high. It is observed that with $q = 0.5$, a high torque to volume ratio may be achieved, but the torque ripple can be high.

High torque would be achieved with $q = 0.5$, but these $q = 0.5$ machines seem to have the worst torque ripples and also high cogging torques. Figure 7 shows that the 12-slot-8-pole ($q = 0.5$) and 12-slot-16-pole ($q = 0.25$) machines produce higher torque ripples than the others with semi-closed slot structures. Skewing might help to reduce this effect. Table II gives the least common multiplier LCM values for concentrated winding fractional slot machines.

Fig. 6 also gives the cogging torque values with different relative magnet width for machines with 12-slots with semi-closed slot opening. Relative slot opening width is 0.08 of the slot pitch.

The torque ripples (% of the average torque peak-to-peak value) for machines with 12-slots with semi-closed slot opening are shown in Fig. 7. As the figure indicates, the

TABLE II
THE LEAST COMMON MULTIPLIER LCM VALUES FOR CONCENTRATED WINDING FRACTIONAL SLOT MACHINES [6]

$Q_s \backslash 2p$	2	4	6	8	10	12
3	6	12	6	24	30	12
6		12	18	24	30	36
9			18	72	90	36
12				48	60	72
15					30	60
18						36

$Q_s \backslash 2p$	14	16	20	22	26	28
3	42	48	60	66	78	84
6	42	48	60	72	78	84
9	126	144	180	198	234	252
12	84	48	60	132	156	168
15	210	240	60	330	390	420
18	126	144	180	198	234	252
21	42	336	420	462	546	84
24		96	120	264	312	168

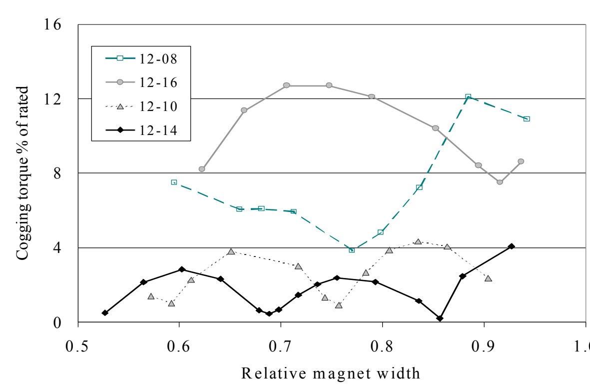

Fig. 6. Cogging torques (% of the rated torque, peak-to-peak values) as a function of the relative magnet width for the 12-slot stator with a semi-closed slot.

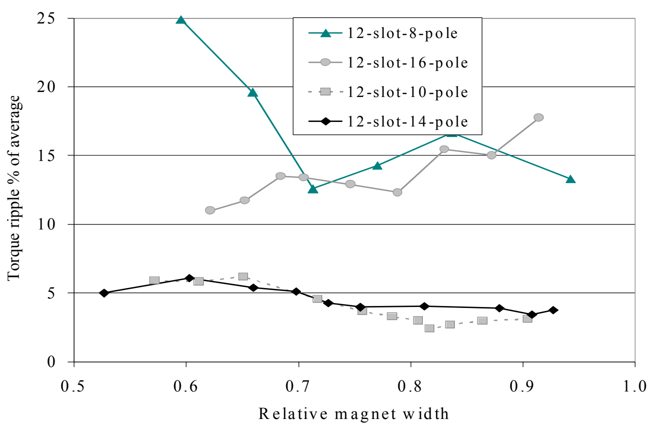

Fig. 7. Torque ripples (% of the rated torque, peak-to-peak values) as a function of the relative magnet width for the 12-slot stator with a semi-closed slot.

machine torque ripple may be seriously dependent on the relative magnet width. The best choice for the magnet width also depends on the stator construction and, hence, it is difficult to give exact guidelines for the relative magnet width in different cases, contrary to the case of integer slot machines, in which it is possible to give exact recommendations of the magnet width. As Fig. 7 indicates, each construction may have different values for the best relative magnet widths. For instance, the 12/8 machine produces torque ripple minima at $w = 0.72$ and 0.95.

VI. CONCLUSION

The following requirements or at least some of them are usually set for desirable machine constructions; the machine must have a large fundamental winding factor, it should produce the maximum torque and a low torque ripple, and further, unbalanced magnetic pull should be avoided and the machine should use a low amount of PM material. To achieve all these requirements, the best general choice could be a machine with $q = 0.4$.

A machine with $q = 0.4$ has a relatively good winding factor and pull-put torque (p.u). The $q = 0.4$ machine could be a good choice because of the high torque ripple of the $q = 0.5$ machines. Machines with $q \approx 0.33$ have the smallest cogging torque and torque ripple, but the pull-out torque (p.u) is also quite small.

The $q = 0.4$ machine could be the best design to obtain a low cogging torque and torque ripple. As the Fig. 6 and 7 indicate, 12/10 machine has a low cogging torque and also small torque ripple compared for example with the 12/14 machine, which has a low cogging torque and torque ripple, but the pull-out torque is only 1 p.u.

The best relative permanent magnet width changes depending on whether the machine is operating at no-load or with a load. Fig. 6 and 7 show machines with 12-slots and with different pole numbers in both these situations. As the figures indicate, the 12/10 machine gives a minimum cogging torque with the relative magnet width of 0.76 and minimum torque ripple at 0.82. Changing the slot opening width causes the change of the position of minima [6]. The best choice for the relative magnet width could be 0.75.

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