LOW SPEED PERMANENT MAGNET SYNCHRONOUS MOTOR COMPARISON - CONCENTRATED AND DISTRIBUTED WINDINGS

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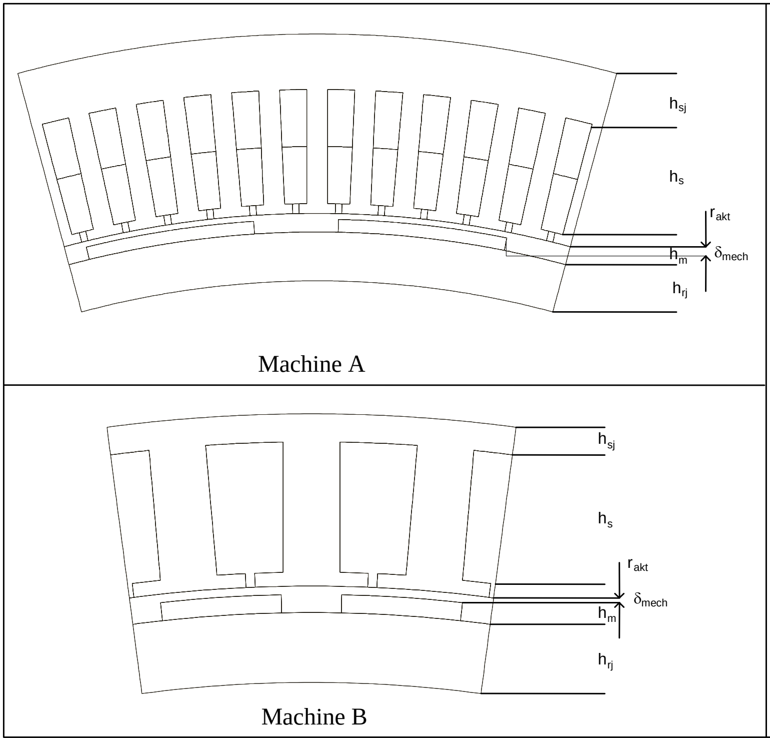
1 INTRODUCTION

The interest in permanent magnet synchronous machines has recently gained interest in industrial applications [1]. As an example, high efficiency, no rotor losses and high power density resulting from elimination of rotor windings have made permanent magnet motor a leading candidate for the direct drive industrial application. The direct-driven synchronous motor for low speed application provides better performance when compared to conventional induction motor equipped with gears. By eliminating the gearbox, the user saves space and installation costs due to fewer mechanical components. The task focuses on comparing concentrated fractional winding design with the distributed winding design for permanent magnet synchronous machine for low speed. The design process investigates surface mounted permanent magnet (SMPM) synchronous machine with same active diameter and iron length.

2 PM SYNCHRONOUS MACHINE DETAILS

The core configurations of the investigated permanent magnet synchronous machines with different winding arrangements are depicted in **Figure 1**. The design parameters of the machines are listed in **Table 1**. The nominal speed of the motor is 300 min^{-1} and the motor dimensions are large: the active radius is 300 mm. Both motors are surface mounted type permanent magnet machines as given in **Table 1** and the teeth of the machine are designed with rectangular shape. The total slot area of Machine A with distributed winding is larger than that of Machine B with concentrated winding. Recently there has been a revival of interest in a fractional slot SMPM made with concentrated windings. With such winding arrangements, the end connections are very short, the winding losses are significantly reduced and the slot fill factor is high. Furthermore there is a reduction in the joule losses and the efficiency of the motor can be increased when compared to the traditional integral slot windings [2]. Both the machines are modelled in the finite element tool by a segment of one elementary machine, due to the magnetic symmetry that is present. The design layout is shown in **Figure 1**.



r_{akt}	Active radius
h_{sj}	Stator yoke height
h_s	Stator slot height
h_m	Magnet height
h_{rj}	Rotor yoke height
δ_{mech}	Airgap length

Figure 1: Geometry of PMSM
- Machine A with distributed winding (q = 2)
- Machine B with distributed winding (q = 0,5)

Table 1: Design parameters of the two machines

Winding arrangement		Machine A	Machine B
No. of pole pairs		12	24
No. of slots per pole per phase q		2	1/2
Active radius r_{st}	[mm]	300	300
Active length	[mm]	146	146
Stator outer diameter	[mm]	355	337
Speed	[min^{-1}]	300	300
Air gap (mechanical clearance)	[mm]	1,8	1,8
Height of the magnet	[mm]	3,9	3,9

3 WINDING CONFIGURATION

High number of poles is preferred when considering low speed direct driven machines. Different winding configurations are investigated. Distributed windings with $q = 2$ and concentrated windings with $q < 1$ were calculated, where q is the number of slots per pole per phase. The fundamental winding factor for the chosen distributed winding is 0,933 and for the concentrated winding with chosen pole-slot combination is 0,866. There are several methods to determine the winding factor of the fractional slot windings. E.g., the winding factors for single and double layer elementary machines are given in [3]. The distribution of the phase windings are shown in **Table 2**. Concentrated windings with double layer are used since they have better properties considering end windings and the sinusoidal induced voltage waveform [4]. For more numbers of slot-pole combinations the winding layouts for concentrated windings are investigated in [5].

Table 2: Distribution of phase windings of the machines

Slots	1	2	3	4	5	6	7	8	9	10	11	12	
Machine A	v'	v'	u	u	w'	w'	v	v	u'	u'	w	w	…
	v'	u	u	w'	w'	v	v	u'	u'	w	w	v'	…
Machine B	w'/v	v'/u	u'/w	w'/v	v'/u	u'/w	…						

4 NUMERICAL CALCULATION

The numerical calculation is performed using finite element software FEMAG. By using finite element method (FEM) it is possible to solve electromagnetic state of machine. Due to the requirements of expected output, the mesh must be generated depending on the parameters to be examined. Computations on FEM are made for several quantities like field, flux, torque, inductances, etc. The simulations for both the distributed winding and concentrated winding are investigated. The **Figure 2** shows the magnetic field lines of an elementary machine representing Machine A.

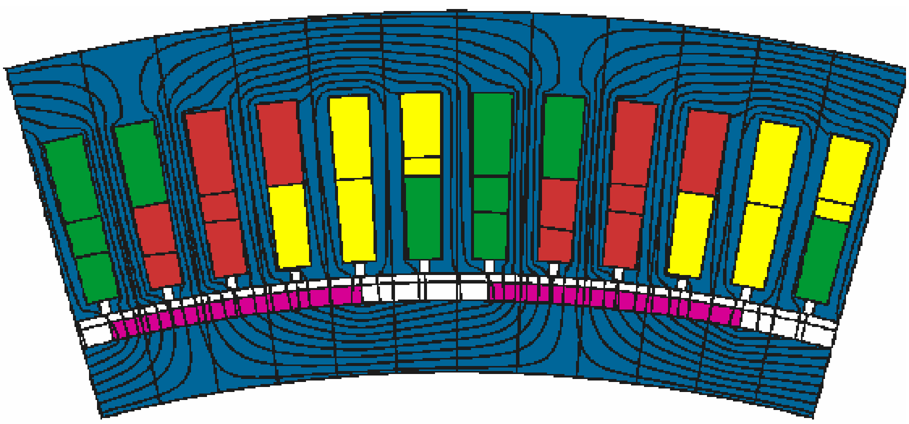


Figure 2: Flux lines for Machine A

The **Figure 3** shows the magnetic field distribution in a sector representing Machine B.

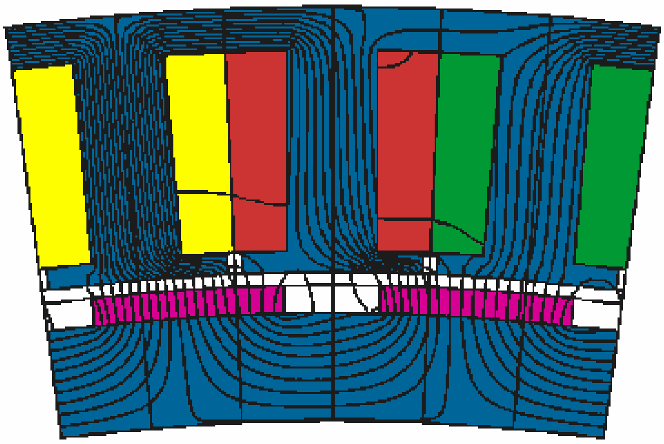


Figure 3: Flux lines for Machine B

5 RESULTS

Designs with different winding configurations and the values of induced voltage, stator current, resistance, inductance and copper losses were compared. Due to the moderate frequencies, the iron losses of the stator and rotor were neglected. **Table 3** gives the different data of the two designs. The number of turns in the coils was determined so that the induced voltages for both designs were nearly equal.

Table 3: Comparison between two winding configurations

		Machine A	Machine B
Stator voltage (U_a)	[V]	394,5	409,8
Stator current (rms) (I_a)	[A]	80,08	85,277
Flux density	[T]	0,934	0,933
Resistance	[Ohm]	0,156	0,125
Inductance	[mH]	6,506	3,976
Torque	[Nm]	2521	2521,5
Copper volume	[cm^3]	4795,6	2549,9
Mech. power	[kW]	79,2	79,22
Power loss	[kW]	2,997	2,724
Power factor		0,867	0,782
Efficiency		0,952	0,943

The result indicates that the Machine B has a larger angle between the stator current and the stator voltage, and accordingly, the power factor is poorer than for Machine A having the same torque and mechanical output power.

The copper loss in windings may be represented by

$$P_{cu} = 3 \cdot \frac{w_s \cdot (l_{Fe} + l_{endw})}{\sigma_{cu} \cdot A_{cu}} \cdot I^2 \quad , \tag{1}$$

where σ_{cu} is the copper conductivity, w_s is the number of turns per phase, l_{Fe} and l_{endw} are the length of iron and end winding and A_{cu} is the copper area per conductor. For motor operation we have

$$P_{elec} = P_{mech} + P_{loss} \quad , \tag{2}$$

where P_{elec} is the electrical input power, P_{mech} is the mechanical output power and P_{loss} are the losses that include iron loss and copper loss [6]. Finally the efficiency and the power factor of the machine were computed. The dimensions of both machines are shown in **Figure 4**. It shows that for the machines having same active length and active diameter, the concentrated wound machine has shorter end windings and hence the volume of the copper is less when compared to distributed wound machine as shown in **Table 3** and thus losses can be reduced significantly. But in this design the losses of both machines are nearly the same. This is due to the presence of harmonics in the current sheet of the stator that counteracts the losses of Machine B.

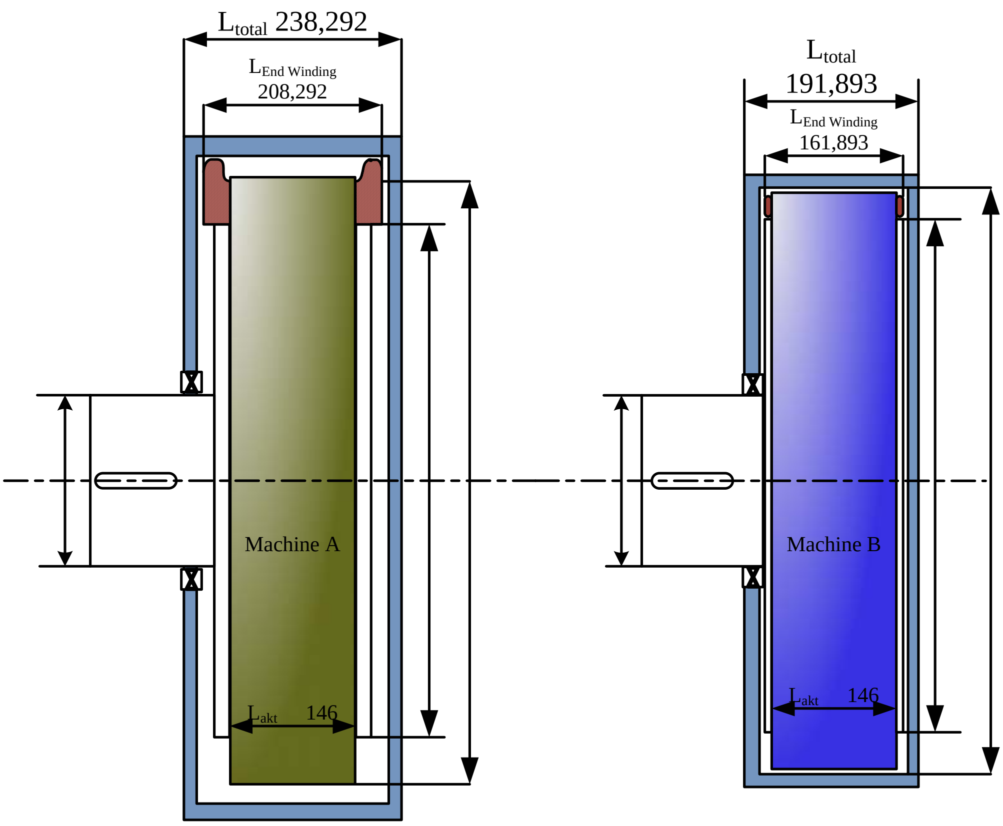


Figure 4: Dimensions in mm of Machine A and B for P_{mech} = 79,23 kW and speed = 300 min^{-1}

6 CONCLUSION

In this report FEM-based calculations on two permanent magnet synchronous machines for distributed winding and concentrated winding were shown. The performance of the machine with concentrated winding is superior, because the minimization of the copper volume is reducing power loss and manufacturing costs. The advantages of preferring the concentrated winding concept for low speed application were given. Using permanent magnet motor also means higher overall efficiency and less maintenance. The direct drive motor also facilitates installation and allows efficient use of floor space.

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