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Design of Permanent Magnet Synchronous Motor

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Abstract— Permanent magnet synchronous motors (PMSMs) have been widely used in many industrial applications. Due to their compactness and high torque density. The PMSMs are particularly used in high-performance drive systems such as the submarine propulsion. The permanent magnet synchronous motor eliminates the use of slip rings for field excitation, resulting in low maintenance and low losses in the rotor. The PMSMs have the high efficiency and are appropriate for high performance drive systems such as CNC machines, robotic and automatic production systems in the industry. Generally, the design and construction a PMSM must consider both of the stator and rotor structures in order to obtain a high performance motor. However this paper focuses only on the design of the permanent magnet rotor and uses the stator structure from an existing induction motor without changing the windings. That is, the squirrel cage rotor is replaced by a newly designed permanent magnet rotor. This paper discusses design of PMSM. MATLAB tool is used to compute the design parameters for the given PMSM machine.

Index Terms— PMSM, MATLAB.

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1 INTRODUCTION

THIS Permanent magnet synchronous motors finds applications in several areas such as traction, automobiles, robotics and aerospace technology. The power density of permanent magnet synchronous motor is higher than induction motor with the same ratings due to the no stator power dedicated to the magnetic field production. Nowadays, permanent magnet synchronous motor is designed not only to be more powerful but also with lower mass and lower moment of inertia.

Permanent magnet synchronous motor (PMSM) is a class of synchronous motor that high magnet material is used to magnetize, it has characteristics of high efficiency, simple structure, easy to control and so on. Inverter fed PMSM drive systems have made it come true to eliminate the physical contact between the mechanical brushes and commutators, so it have become a viable choice for motion control applications such as robotics, numerically controlled machine tools, electric propulsion, aerospace, and many more. With the fast development of power electronic and decreasing price of electrical parts and apparatus, inverter fed PMSM have been widely used in industry.

2 CONSTRUCTION DETAILS

The construction details of Permanent Magnet Synchronous Motor are discussed below.

2.1 Air Gap Flux Density

For designing the stator geometry, methods can be utilized that are well established from e.g. asynchronous motor design. This has therefore not been studied in the present work. The focus is rather on1 the permanent magnet rotor design and on special demands for utilizing the switched stator winding technique. Furthermore a slotted stator is assumed. The air-gap flux density is limited by the saturation of the stator core. In particular the peak flux density is limited by the width of the teeth while the stator back determines the maximum total flux. Besides the allowable saturation level is dependent on the application. Generally the flux density is lower in high efficiency machines and higher in machines designed for maximum torque density. The peak air-gap flux density lies typically in the range 0.7–1.1Tesla. It should be noted that this is the total flux density, i.e. the sum of rotor and stator fluxes. This means that the rotor flux can be chosen higher if the armature reaction is smaller implying higher alignment torque. To achieve a great reluctance torque contribution however, the stator reaction must be large. The machine parameters give that a large m and small inductances L, are required to obtain mainly alignment torque. This is usually desirable for operation below base speed as high inductances lower the power factor cos(Ø).

2.2 Permament Magnet Materials

There are many devices in which magnets play a significant role so it is very important to improve properties of these materials. Currently attention is focused on materials based on rare earth metals and transition metals. These materials allow to obtain permanent magnets with high magnetic properties. Depending on the technology magnets are characterized by different magnetic and mechanical properties and show different corrosion resistance.

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Neodymium Iron Boron (Nd2Fe14B) and Samarium Cobalt (Sm1Co5 and Sm2Co17) magnets are the most advanced commercialized permanent magnet materials available today. Within each of these classes of Rare Earth Magnets are a wide variety of grades. Neodymium Iron Boron magnets were commercially introduced in the early 1980s. They are widely used today in many different applications. The cost of this magnet material (on a dollars per energy product basis) is comparable to that of Ferrite magnets. On a dollars per pound basis, the cost of Neo magnets is about 10 to 20 times that of Ferrite magnets.

Some important properties used to compare permanent magnets are: remanence (M_r), which measures the strength of the magnetic field; coercivity (H_{ci}), the material's resistance to becoming demagnetized; energy product (BH_{max}), the density of magnetic energy; and Curie temperature (T_C), the temperature at which the material loses its magnetism. Neodymium magnets have higher remanence, much higher coercivity and energy product, but often lower Curie temperature than other types. Neodymium is alloyed with terbium and dysprosium in order to preserve its magnetic properties at high temperatures. The table below compares the magnetic performance of neodymium magnets with other types of permanent magnets.

Table 1: Comparison of properties of NdFeB and Sm-Co magnets

Property	NdFeB	Sm-Co
Remanence (T)	1–1.3	0.82–1.16
Coercivity (MA/m)	0.875–1.99	0.493–1.59
Permeability	1.05	1.05
Temperature coefficient of remanence (%/K)	–0.12	–0.03
Temperature coefficient of coercivity (%/K)	–0.55..–0.65	–0.15..–0.30
Curie temperature (°C)	320	800
Density (kg/m^3)	7.3×10^3–7.5×10^3	8.2×10^3–8.4×10^3
Flexural strength (N/mm^2)	250	150
Compressive strength(N/mm^2)	1100	800
Tensile strength (N/mm^2)	75	35
Electrical resistivity (Ω·m)	$(110–170)\times10^{-6}$	86×10^{-6}
Energy product (Bhmax)	32-53	18-33

2.3 Parameters of PMSM

For the design of the Permanent Magnet Synchronous Motor (PMSM), the permanent magnet rotor is constructed based on the stator frame of a three-phase induction motor without changing the geometry of stator and the winding. The specification and geometry are shown in Table 2.

Table 2 Simulation Parameters of PMSM

Designation	Unit	Value
Speed	Rpm	1500
Frequency	Hz	50
No. of poles	-	4
Stack length	Mm	51.4
Internal diameter	Mm	90
External diameter	Mm	146
No. of slots	-	36

3 PMSM Design Procedure

The PMSM Design is being carried out by using MATLAB. Following equations are used to calculate the copper losses, back e.m.f., iron losses and self and mutual inductance.

The pole pitch can be calculated by the formula,

$$\tau_p = 2\pi R_a/2p$$

Total flux can be calculated by the formula,

$$\varphi = \frac{2}{3} * B_g \tau_p \, L_z pN * phase$$

Back EMF can be calculated by the formula,

$$E = {}^{\partial\varphi}/_{\partial t}$$

The equation to calculate copper losses is given below

$$P_j = 3R_s I^{\,2}$$

Stator resistance can be calculated by the formula,

$$R_s = \rho * L / S$$

Total length of copper per phase can be calculated as,

$$L_{end} = \frac{\frac{\pi}{2} 2\pi\left(R_a + {}^{h_{enc}}/_{2}\right)}{2p}$$

$$L_{total} = 2(L_z + L_{end})$$

Calculations for Self and Mutual Inductances:

The inductance L can be defined as the ration of the flux linkages to the current I generating the flux, this has the units of henrys (H), equal to a weber per ampere. Inductors are devices used to store energy in the magnetic field, analogous to the storage of energy in the electric field by capacitors. Inductors most generally consist of loops of wire, often wrapped around a ferrite or ferromagnetic core, and their value of inductance is

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a function only of the physical configuration of the conductor along with the permeability of the material through which the flux passes.

A procedure for finding the inductance is as follows:
1. Assume a current *I* in the conductor.
2. Determine B using the law of Biot-Savart, or Ampere's circuital law if there
is sufficient symmetry.
3. Calculate the total flux *tot* ϕ linking all the loops.
4. Multiply the total flux by the number of loops to get the flux linkage:

Now Slot pitch can be calculated by the formula,

$$\tau_d = 2\pi R_a / N_s$$

Self Inductance can be calculated by the formula,

$$L = \mu_0 N^2 \tau_p L_z / 2e$$

Mutual Inductance can be calculated by the formula,

$$M_{12} = \frac{\mu_0 N^2 L_z (\tau_p - \tau_d)}{2e}$$

$$M_{13} = \mu_0 N^2 L_z \left(\tau_p - 2\tau_d\right)/2e$$

$$L_{eq} = 3L + 4 * M_{12} + 2 * M_{13}$$

$$L_{ab} = 2L_{eq}$$

Torque can be calculated by the formula,

$$Torque\Gamma \; = \; 4\,pq \cdot NI \cdot B_e L_z R_a$$

Table 3: Input of required terms

Parameters	Symbol	Value
Frequency	f	50
No. of slots/ pole/ phase	q	3
Internal radius of stator	Ra	45
No. of pole pair	p	2
No. of turn	N	74
Height of stator	*henc*	9.6
Stack Length	Lz	51.4
Magnetic flux in air gap	Be	0.857
Diameter of copper wire	D	0.55
No. of slots	Ns	36
Height of magnet+air gap	e	7

4 Results and Discussions

A stand alone solar PV system has been modeled for the PMSM drive used in water pumping system. Solar PV water pumping systems are simple, reliable, conserve energy and needs less maintenance. The torque requirement for this water pumping application is 3.6 N-m.

The design of PMSM motor is carried out by evaluating the required parameters using MATLAB as computing software. Following tables shows the result obtained from the calculations as per the equations provided earlier. Table 4. Gives the parameter evaluated for the PMSM motor with SmCo as a permanent magnet material. The magnetic flux density in air gap is taken as 0.8 Tesla.

Table 4: Output values for SmCo material

Parameters	Symbol	Output Values
Pole pitch	τ_p	48.86
Flux	ø	637.17
Copper Losses	P_j	59.34
Stator resistance	R_s	8.79
Length of Copper wire	L_{total}	124.32
Slot pitch	τ_d	5.43
Self Inductance	L	1.23
Mutual Inductances	M_{12}	1.097
	M_{13}	0.96
Equivalent Inductance	L_{eq}	10.01
Inductance at Phase a	L_{ab}	20.02

Table 5: Gives the parameter evaluated for the PMSM motor with NdFeB as a permanent magnet material. The magnetic flux density in air gap is taken as 1 Tesla.

Table 5: Output values for material NdFeB

Parameters	Symbol	Output Values
Pole pitch	τ_p	41.62
Flux	ø	633.31

Copper Losses	P_j	54.5195
Stator resistance	R_s	8.077
Length of Copper wire	L_{total}	114.223
Slot pitch	τ_d	4.6251
Self Inductance	L	1.0517
Mutual Inductances	M_{12}	0.9348
	M_{13}	0.8180
Equivalent Inductance	L_{eq}	8.53
Inductance at Phase a	L_{ab}	17.6

It is found that the design with NdFeB as ac PM rotor material the flux produced in the air gap is improved, leading to the reduction in internal radius of stator to 26.50 mm as compare to 31.11 mm as in case of the SmCo PM rotor material. Also the effective copper losses in the NdFeB are reduced by 8.124% as seen in the results.

For the SmCo as a permanent magnet material the flux is found to be equal to 637.17 mWb which will be a sinusoidal varying quantity as shown in the following figure.

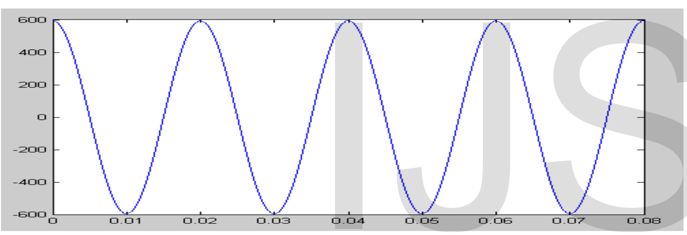

Figure 1: Flux waveforms for PM material SmCo

For the NdFeB as a permanent magnet material the flux is found to be equal to 633.31 mWb which will be a sinusoidal varying quantity as shown in the following figure.

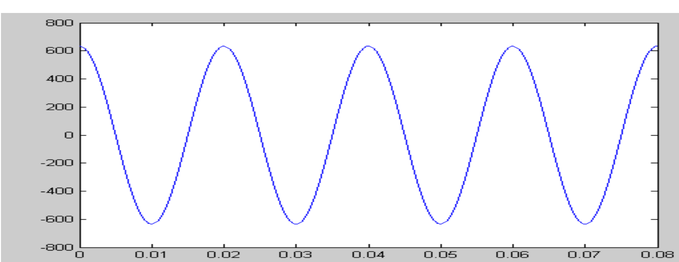

Figure 2: Flux waveforms for PM material NdFeB

5 Conclusion

Permanent magnet synchronous motors (PMSMs) have been playing an important role in high performance drive systems. However, most of the PMSMs used in the industries have been imported. To reduce such import, there is the need to develop technical knowhow on the design and construction of the PMSMs. This paper takes the first step towards this direction. Generally, the design and construction a PMSM must consider both of the stator and rotor structures in order to obtain a high performance motor. However this paperfocuses only on the design of the permanent magnet rotor and uses the stator structure from an existing induction motor without changing the windings. That is, the squirrel cage rotor is replaced by a newly designed permanent magnet rotor.

A MATLAB based programme is developed which gives the design parameters for the PMSM motor including the self and mutual inductances, Torque produced, Copper losses for two different permanent magnet rotor materials. These parameters are evaluated to determine the performance of the PMSM motor for the water pumping application.

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