The Design and Comparison of Salient Pole and Permanent Magnet Synchronous Machines

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Abstract

The paper presents the analysis and the comparison of salient pole with field winding and of peripheral winding synchronous electrical machines, presenting important advantages. Neodymium alloy magnet rotor structure has been considered and compared to the salient rotor case. Salient Pole Synchronous Machine (SPSM) and Permanent Magnet Synchronous Machine (PMSM) were designed as the plate values to remain in constant. The eddy current effect on the windings is taken into account during the design and the efficiency, output power and the air-gap flux density obtained after the simulation were compared with each other. Design optimization has been performed via MAXWELL program based on the finite element method.

In this study, the importance of the design of electrical machines and the determination of the criteria is emphasized. This paper will be a helpful resource in terms of examination and comparison of the basic structure and magnetic features of the SPSM and PMSM.

1. Introduction

Synchronous Machines (SM) are commonly used as generators especially for large power systems, such as turbine generators and hydroelectric generators in the grid power supply. SMs are primary energy conversion devices of the word's electric power system which rotates at constant speed in the case of both generator and motor operations. And also SMs can draw either a lagging or a leading reactive current from the supply system. These are the reasons why the SMs are commonly preferred.

Instead of excitation of the windings, Permanent Magnet (PM) has been started to use because of the significant improvements in power electronics and PM materials. PM machines are preferred nowadays because of their characteristics of high power density, high torque, high acceleration / torque ratio, easy launch, high efficiency, and compactness [1].

There are many studies in the literature on SPSM [2-4] which is used especially used in power distribution systems and PMSM [5-8]. And also the optimizations of these machines are made in genetic algorithms and finite-element based programs [9-11].

In this study, examination of SPSM and PMSM were performed using the Maxwell program so that the output power and speed to remain constant. Design of two different type machines which are wound rotor and PMSM is made in order to achieve maximum efficiency. In the design of the SPSM, classic dc windings and damper windings are used on the pole surfaces. In the design of PMSM, surface mounted rotor structure was preferred which has a higher efficiency compared to embedded type rotor structure [12]. This study is a new study in terms of design and comparison of PMSMs and SPSMs.

2. SPSM

There are two types of rotor structures in SMs: round or cylindrical rotor and salient pole rotor. Generally, round rotor (Non-salient pole generator) structure is used for high speed and large power SMs, such as steam turbine generators and nuclear power plants, while salient pole structure is used for low speed and small and mid-size power applications, such as hydroelectric and wind turbine generators and it is also used for emergency power supply and pumps and ship propulsion.

The double-layer winding is often used to wind the armature of a synchronous generator as performed in this study. A double-layer winding requires as many identical coils as there are slots in the stator. Obviously a large current and hence a large conductor diameter leads to high eddy current losses unless the conductor is subdivided into twisted fine strands. So in this study, eddy effect on the windings is taken account. The stator (armature) of most synchronous generators is wound with three distinct and independent windings to generate three-phase power. The three-phase windings are connected to form as a star (Y) connection.

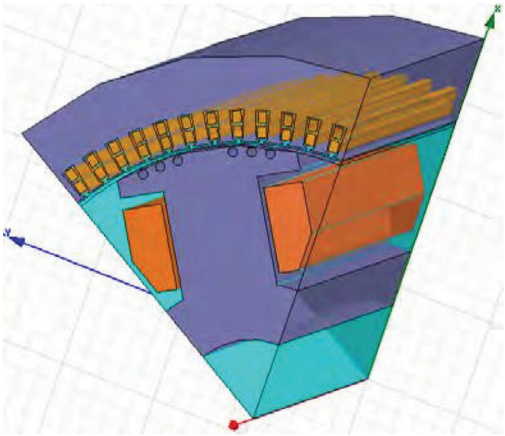


Fig. 1. Rotor pole and windings.

Rotor windings, as shown in Fig. 1, are consisted of axial windings wrapped around the shoe foot. These windings allow the generation of the magnetic induction in the rotor. Compared to PMSM, SPSM has copper and eddy losses in the rotor even though they have been generated the same flux density. Also, the area covered by the windings is larger than PM's in regard to the generated magnetic flux density. In addition to these windings, SPSM has damper windings which allow the re-synchronization when synchronous operation of the machine is broken.

In self-excited generators, shaft-mounted exciter and rectifier (diodes) generate the required field current. The shaft-mounted exciter is itself excited from a stationary winding. The fact that unlike the stator, the rotor field is fed from a relatively low power, low voltage circuit has been the main reason why these machines have the field mounted on the rotating member and not the other way around. Moving high currents and high power through the collector rings and brushes (with a rotating armature) would represent a serious technical challenge, making the machine that much more complex and expensive.

3. PMSM

A PM can produce magnetic field in an air-gap with no excitation winding and no dissipation of electric power. And it has clasic three phase winding in the stator which is same as SPSM, and PMs which mounted on the surface of the rotor. External energy is involved only in changing the energy of magnetic field, not in maintaining it. PMSMs, avoid loss of excitation, high torque and / or output that have the power, better dynamic performance, structure is advantageous in terms of simplicity and is easy to maintenance [13]. However, the cost is high, meet the high flux density of the alloy cannot be found, alloy material the use of more high value of flux, processing, in addition to the difficulties in producing the assembly and, this brings additional power electronics circuits have disadvantages such as expensive. PMSMs are used for wind power plants. It is possible to combine PM wind generators for hybrid technologies such as wind-diesel, wind-photovoltaic etc. [14]. The most widely used PMs nowadays in electrical machines are [13]:

- Alnicos : Al, Ni, Co, Fe;
- Ceramics (Ferit):Barium Ferrite and Strontium;
- Rare Earth Magnets: Samarium-Cobalt (SmCo), Neodymium-Iron-Boron (NdFeB).

Table 1. PM materials and properties

	Br (T)	**Hc (kA/m)**	**Bh_{max} (kJ/m^3)**	**Max. Oper. Tem. (°C)**	**Density (g/cm^3)**	**Relative Permability (μ/μ_0)**
Alnico5	1,25	50,93	43,8	540	7,28	2,2
Alnico8	0,83	131,3	43,8	540	7,3	2
Alnico9	0,7	151,2	39,8	540	7,28	1,5
SmCo24	1	708,2	191	350	8,3	1,05
SmCo28	1,07	819,67	222,8	380	8,3	1,05
NdFeB30	1,1	843,54	238,7	300	7,42	1,09
NdFeB35	1,23	899,25	278,5	300	7,4	1,09

Table I compares some relevant properties for a few common PM materials. Br is the remanence flux density, Hc is the coersitive field strength, BH is the maximum energy density. In the present case NdFeB was chosen because of its superior properties. The ideal shape of a single magnetic pole is an arc However, in large machines with nominal power of 100 kW or more, the diameter is several meters and the magnet shape is approximately rectangular [5]. Because of the mutual repulsion each magnetic pole must be of a size which can be mounted as a single piece. The added cost of obtaining magnets is of little significance during the manufacturing process. Glue cannot be used, because the temperature coefficients of iron and magnet material are different. Because of the susceptibility to corrosion magnets must be coated with nickel. When dimensioning the magnets, it is necessary to ensure that the operating point leaves a proper margin against demagnetization in all situations.

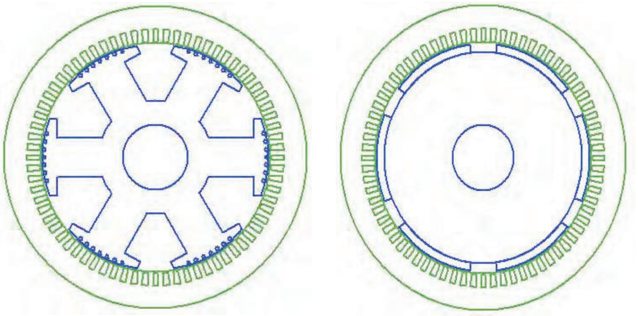
4. FEM Analysis of SM

Electrical machines required an accurate mathematical model for system simulation and performance evaluation. Detailed knowledge of the air-gap flux distribution of an SM plays a very important role in a safe estimation of the characteristics of the machine's torque and efficiency. The distribution of magnetic flux can be calculated analytically for very simple geometries. In most cases, the distribution of magnetic flux is obtained through the use of numerical methods like Finite Element Method (FEM), Finite Difference Method (FDY) or a Boundary Elements Method (BEM). In this study, magnetic analysis of the designed machines has been investigated using Maxwell 2D program. The simulation was completed using the following steps;

1) Geometric model creation,
2) The appointment of the materials that make up the structure of the machine,
3) Boundary conditions and mesh process,
4) The appointment of currents in windings,
5) Analyze,
6) Examination of the results.

5. The Results of the Analysis & Discussion

In the study, the two design shown as Fig. 2 have been analyzed for the general engineering structures, to be able to define the path pursed by the magnetic fluxes, determine the flux densities and the calculate the storage magnetic energies and intensities. The finite element network (mesh) is built to be thickly in the air gap and some more rare in the iron cores. Minimum number of elements is 2000 on the air-gap and 1000 on the other surfaces. Requested data on the machine are given in Table 2. All analysis was made according to the value of constant power (538kW). The dimension of the designed machines depends on such as the type of current, the rated speed, the coefficients of generator windings and generator output power.



a) SPSM b) PMSM

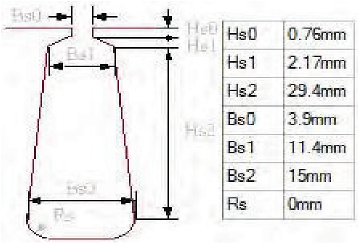
Fig. 2. General view of the designed machines

The rotor and the stator core material made of Steel 1010 and the copper coils are placed into stator slots.
As a result of finite element analysis, 72 slotted, output powers and speeds that are same, the shape and dimensions of the stator slots that are same but have different number of turns and winding structure PMSM and SPSM are determined using Maxwell Program.

Table 2. General Parameters

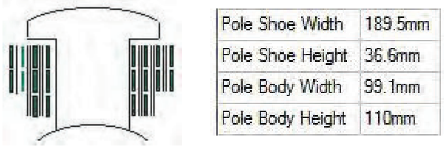
Rated Output Power (kW)	538
Rated Voltage (V)	400
Number of Poles	6
Rated Speed (rpm)	1000
Frictional and Windage Losses (W)	2600
Rated Power Factor	0.98
Type of Load	Fixed Power
Operation Temperature (˚C)	115

Stator slots and Rotor shapes and sizes of the machines are determined as Fig. 3-5. The special form is given to the top of the SPSM's rotor pole to be able to obtain the sinus form in the air-gap. The other design results of the machine analysis were obtained as in Table 3-5.



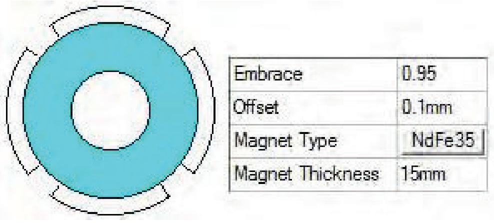
Hs0	0.76mm
Hs1	2.17mm
Hs2	29.4mm
Bs0	3.9mm
Bs1	11.4mm
Bs2	15mm
Rs	0mm

Fig. 3. Stator slot dimensions



Pole Shoe Width	189.5mm
Pole Shoe Height	36.6mm
Pole Body Width	99.1mm
Pole Body Height	110mm

Fig. 4. SPSM pole dimensions



Embrace	0.95
Offset	0.1mm
Magnet Type	NdFe35
Magnet Thickness	15mm

Fig. 5. PMSM pole dimensions and PM material

Table 3. Geometrical Parameters of the Stators

Number of Slot	72
Outer Diameter (mm)	736.6
Inner Diameter (mm)	558.8
Length of the Core (mm)	395
Stacking Factor	0.9
Steel Type	Steel 1010

The two models are compared regarding flux density distribution under maximum torque conditions. Fig. 6 depicts the magnetic flux for PM machine while Fig. 7 gives the same result in the salient rotor machine case.

Table 4. Geometrical Parameters of the Rotor

Air-Gap (mm)	3.55
Inner Diameter (mm)	160
Length of the Core (mm)	395
Stacking Factor	0.9
Steel Type	Steel 1010

Table 5. Pole Parameters

PM	Magnet Thickness (mm)	15
	Width of Magnet (mm)	266.965
	Type of Magnet	NdFeB35
SP	Pole-Shoe Width (mm)	189.5
	Pole-Shoe Height (mm)	36.6
	Pole-Body Width (mm)	99.1
	Pole-Body Height (mm)	110

Table 6. Winding Parameters

Feature\Machine Type	**SP**	**PM**
Winding Layers	2	2
Winding type	Half-Coiled	Half-Coiled
Parallel Branches	6	6
Conductor per Slot	9	10
Coil Pitch	11	11
Number of Stands	15	15
Wire Diameter (mm)	1.63 - Round	1.63 - Round

The comparison of the field calculation shows that both models are in quite good agreement and the main difference is that in the PM machine case the flux density distribution is less affected by the machine loading.

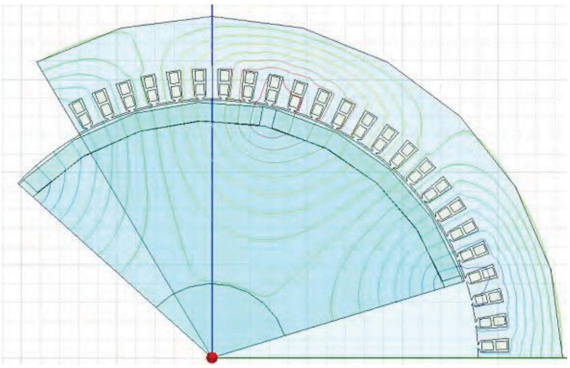


Fig. 6. Flux lines of PMSM

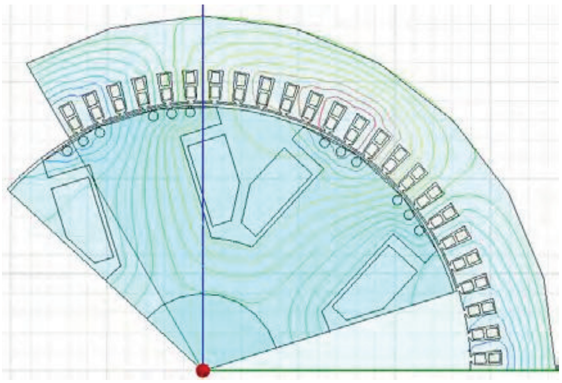


Fig. 7. Flux lines of SPSM

BH curves of NdFeB35 magnet used in the PMSM's rotor and Steel 1010 material used in the PMSM and SPSM's stator and rotor go to saturation points at 1.23T and 2.4T respectively. When these values and the other values obtained with the analysis results (given in Table 7. and Fig. 8-9) are compared, it is seen that the machines operates under the saturation points.

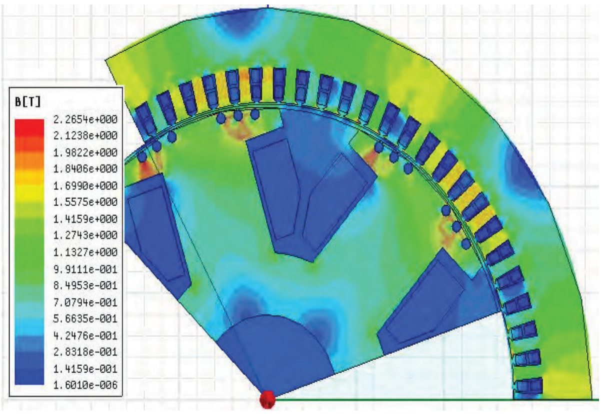


Fig. 8. Magnetic Flux density of the SPSM

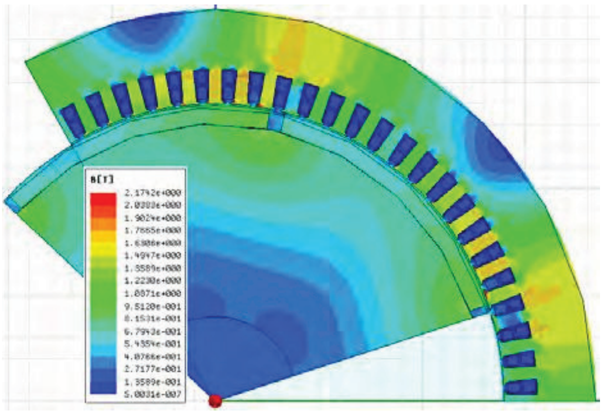


Fig. 9. Magnetic Flux density of the PMSM.

Table 7. Magnetic Data

Magnetic Data	SP	PM
Stator-Teeth Flux Density (T)	2.1325	1.7212
Stator-Yoke Flux Density (T)	1.9637	2.1908
Rotor-Yoke Flux Density (T)	1.7643	0.6853
Air-Gap Flux Density (T)	0.9659	0.7937
Pole Body / Magnet Flux Density (T)	2.0802	0.8356

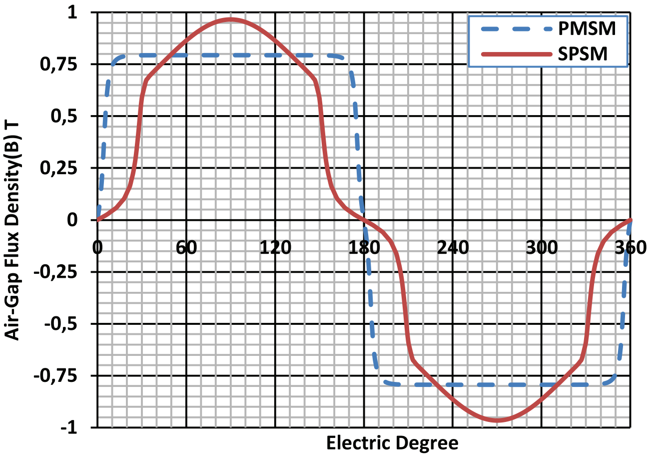


Fig. 10. Air-Gap Flux Density distribution

The flux distribution of rotor completes its path properly (without breaking in the air-gap) through the stator and air-gap. This means that, the air-gap spaces of the designed machines is in the appropriate value. Also, from the performance curves and tables of the machines it is smoothly deduced that the air gap values are in an acceptable range. The change of the air gap flux density is obtained as in Fig. 10. The closer the the flux density in the air gap to the sinusoidal, the better the performance of the machines will get. In the case of the SPSG, the flux distribution at the air-gap appears to be more sinusoidal than PMSM.

Induced winding phase voltages at full load are obtained as given in Figure 11. PMSM and SPSM has same induced winding phase voltages value with 20 electrical degree. The maximum value of induced winding phase voltages is approximately 580V.

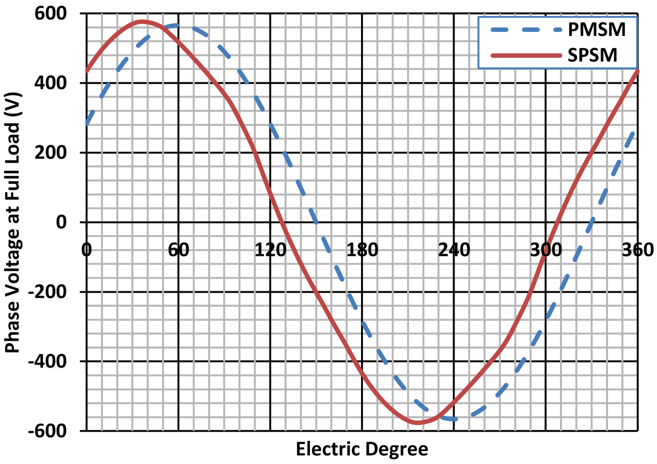


Fig. 11. Induced winding phase voltages at full load.

After the necessary analysis and calculations, all losses of two different synchronous generators at the same power and rotor rpm at the rated load are given in Table 8.

Table 8. Losses at Full Load

Feature\Machine Type	SP	PM
Iron-Core Loss (W)	27.4418	0.10518
Armature Copper Loss (kW)	7.4	8.805
Frictional and Windage Loss (kW)	2.6	2.6
Total Field Losses (kW) *	5.631	-
Input Power (kW)	552.002	549.597
Output Power (kW)	536.342	538.193
Efficiency (%)	97.163	97.9249

* Total field loss is consisted of additional loss, field copper loss and exciter loss.

The efficiency of SPSM is 97.213% without damper winding. After the analysis the shaft torques are obtained almost same. (SPSM is 5.271kN.m and PMSM is 5.224kN.m.)

Table 9. Material Weights (kg)

Feature\Machine Type	SP	PM
Armature Copper Weight	157.254	186.935
Field Copper \ PM Weight	165.34	70.2108
Damper Bar Material Weight	10.2072	-
Damper Ring Material Weight	5.62733	-
Armature Core Steel Weight	362.897	424.096
Rotor Core Steel Weight	293.257	541.946
Total Net Weight	994.583	1223.19

Weights of the SMs that have different rotor structure considering detailed generator geometry are given in Table 9. As it can be seen clearly form the table, SPSM had damper windings is 21.75% lighter than PMSM. The rotor weight of the PMSM can be reduced with different rotor design. When it is economically considered, this ratio is very important.

If efficiency and weight of machine are more important, the selection of SPSM will be more appropriate and economical because, the PM materials are more expensive then copper in the exciter system of the machine. Therefore, the PMSM costs more than SPSM.

Even though the designed machines do not have the same geometrical size and dimensions, when PM was used so as to provide the excitation instead of winding, the following results were obtained:

- ✓ increasing the weight of the engine,
- ✓ easy productivity,
- ✓ rated torque is reduced slightly,
- ✓ output power is increasing and decreasing air-gap flux density.

6. Results

In this study, general and magnetic analysis of SPSM and PMSMs have been made using Maxwell program and the results of the analysis are compared in terms of topology, size, magnetic field, air-gap flux, voltage, torque, losses, weight and efficiency. After the analysis, it is understood that; while the efficiency of SPSM is lower than PMSM's, SPSM is more economical in terms of cost, weight and electronic drive circuits used to control of machines. Even if the usage of the PMSM in lower power applications have the advantage, with a better design, SPSM may be more advantageous than PMSM in high power applications. However, if magnet and semi-conductor technology is improved, the PMSM may have advantage in cost. Therefore, better design of electrical machines is very important in respect to machine efficiency and efficient use of energy.

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