

Halbach array-based design and simulation of disc coreless permanent-magnet integrated starter generator

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Abstract. The functional performance, such as magnetic flux leakage, power density and efficiency, is related to the structural characteristics and design technique for the disc permanent magnet synchronous generators (PMSGs). Halbach array theory-based magnetic circuit structure is developed, and Maxwell3D simulation analysis approach of PMSG is proposed in this paper for integrated starter generator (ISG). The magnetization direction of adjacent permanent magnet is organized in difference of 45 degrees for focusing air gap side, and improving the performance of the generator. The magnetic field distribution and functional performance in load and/or unload conditions are simulated by Maxwell3D module. The proposed approach is verified by simulation analysis, the air gap flux density is 0.66T, and the phase voltage curve has the characteristics of a preferable sinusoidal wave and the voltage amplitude 335V can meet the design requirements while the disc coreless PMSG is operating at rated speed. And the developed magnetic circuit structure can be used for engineering design of the disc coreless PMSG to the integrated starter generator.

1. Introduction

With the development of automotive integration, the integrated starter and generator (ISG) is deemed fit as sustainable alternatives in electricity generation and dynamic equipment [1,2]. ISG is capable of reducing the fuel consumption of hybrid electric vehicle (HEV) which has the function of automatic start stop, power compensation, and high efficiency power output. The disc coreless permanent magnet synchronous generator (PMSG) machine is widely studied in HEV because of their simple structures and low costs compared with general PMSG [3].

The Halbach array is a new type of permanent magnet arrangement, which is especially suitable for the rotor surface adhered the permanent magnet [4]. When the permanent magnet is arranged in Halbach array, the most notable feature is that the air gap flux increases, while the rotor yoke flux decreases, and the sinusoidal air gap magnetic field is obtained [5,6]. These are very beneficial for reducing the motor volume and increasing the power density. These make it susceptible to disc coreless PMSG [7].

There are two methods of electromagnetic analysis for disc coreless PMSG. They are named respectively numerical techniques and analytical techniques [8,9]. The magnetic equivalent circuits (MEC) calculation is a kind of numerical techniques. It is a method to divide the uneven magnetic field in space into the equivalent magnetic circuit of many segments. ANSYS Maxwell 3D is a type of analytical techniques that uses finite element analysis (FEA) to solve electromagnetic problems [10].



In order to improve the design efficiency and precision, the field circuit coupled finite element method is used. The electromagnetic design procedure of disc coreless PMSG involves three steps. Firstly, MEC as a calculation method, the initial size of the disc coreless PMSG is calculated. Secondly, the model built by SolidWorks and imported to the Maxwell. Thirdly, the disc coreless PMSG electromagnetic characteristics are verified by Maxwell 3D analysis [11]. To reduce the weight of the generator and improve the utilization ratio of permanent magnet, the structural design and simulation analysis is presented.

2. Electromagnetic field design and analysis

The disc PMSG also called axial flux permanent magnet machines (AFPM), which is different from cylindrical motor [12]. The magnetic circuit distribution of disc PMSG is very complex. The equivalent magnetic circuit calculation assumes that the magnetic flux in each section of the magnetic circuit is along the cross section and the length distribution. In fact, the existence of a nonuniform distribution of magnetic fields becomes equivalent to multiple magnetic circuits. This will reduce the amount of time, especially in initial structure design. The mechanical and electromagnetic design was accomplished with an example of the rated speed 3000 r/min, the rated power 6 Kw and the rated voltage 300 V disc coreless PMSG. The parameters are shown in table 1. By using the field circuit coupled finite element method, the disc coreless PMSG based on the Halbach array were analyzed.

Table 1. ISG AFPM parameter.

Parameters	Values
Rated Power	6 KW
Rated Voltage	300V
Rated Speed	3000 r/min
Frequency	400 Hz
Rated Power Factor	0.9
Operating Temperature	75°C

2.1. Electromagnetic field calculation

Because of the special structure, the AFPM appears the uneven distribution of the flux density and magnetic circuit at different radius length. In order to accurately calculate the magnetic field distribution, it is necessary to use MEC method to calculate the three-dimensional magnetic field. The main parameters, such as air gap magnetic density distribution and magnetic flux leakage coefficient, can be calculated by three-dimensional magnetic field calculation [13].

ANSYS Maxwell3D can visually show the distribution of electromagnetic fields. The theoretical principle of Maxwell is finite element analysis. The electromagnetic fields have been analysed by Maxwell formulas which obtain a guaranteed solution with appropriate boundary conditions in a finite region of space [14]. Maxwell's formulas are shown as formula (1)-(4).

$$\left\{ \begin{array}{l} \nabla \times H = J + \frac{\partial D}{\partial t} \\ \nabla \times E = -\frac{\partial B}{\partial t} \\ \nabla \times D = \rho \\ \nabla \times B = 0 \end{array} \right. \quad \begin{array}{l} (1) \\ (2) \\ (3) \\ (4) \end{array}$$

Generally, the electromagnetic field of the PMSG varies with the different media. There are the following electromagnetic relations.

$$\begin{cases} D = \xi E & (5) \\ J = \sigma E & (6) \\ B = \mu H & (7) \end{cases}$$

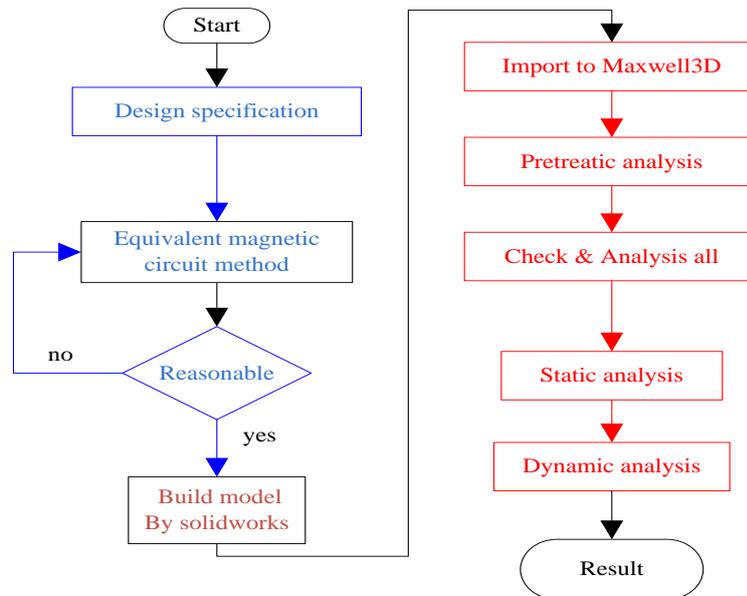


Figure 1. Framework for the design and electromagnetic analysis of PMSG.

As shown in the framework, the electromagnetic field calculation and analysis of disc coreless PMSGs is presented. It can be summed up in three parts. First, initial electromagnetic parameters and geometric dimensions are calculated by MEC calculation. Second, the model is established by SolidWorks and imported into the Maxwell 3D. Last, the operation situation of the generator is obtained by Maxwell 3D. The calculation of electromagnetic field requires the initial estimation of generator line load and magnetic load. Parametric initial estimated will be constantly validated during the calculations. Maxwell 3D is a mighty tool which can be verified the optimum value of the MEC calculation results.

2.2. Structure and electromagnetic analysis

As shown in figure 2(a), the disc coreless PMSG is composed by double-sided rotor and single stator. The Halbach PM rotor symmetrically distribute on both sides to form a closed magnetic circuit structure, thereby reducing the leakage flux of the motor, and improving the utilization of permanent magnets. The rotor consists of 64 PMs bonded the rotor yoke with the material of NdFeB35. The direction of the permanent magnet magnetization is 45 Halbach array as figure 2(b). The rotor array-based Halbach has the magnetic shielding property, which increases the air gap of magnetic field intensity and reduces the yoke of magnetic field intensity. Therefore, the yoke thickness is reduced. The stator PMSG is composed by 24 rhomboidal coils with stucked epoxy as figure 2(c).

It can be seen from the analysis of MEC that the main path of the magnetic circuit is composed of the circumferential path and the axial path. The axial magnetic circuit is composed by the magnetic flux flowing from one PM through the air gap, stator and the yoke to another PM.

The air gap magnetic field is divided into three parts of the air gap magnetic field. As shown in figure 3, the area of I is the yoke region. II describes the air gap region. III represents air gap and the winding region.

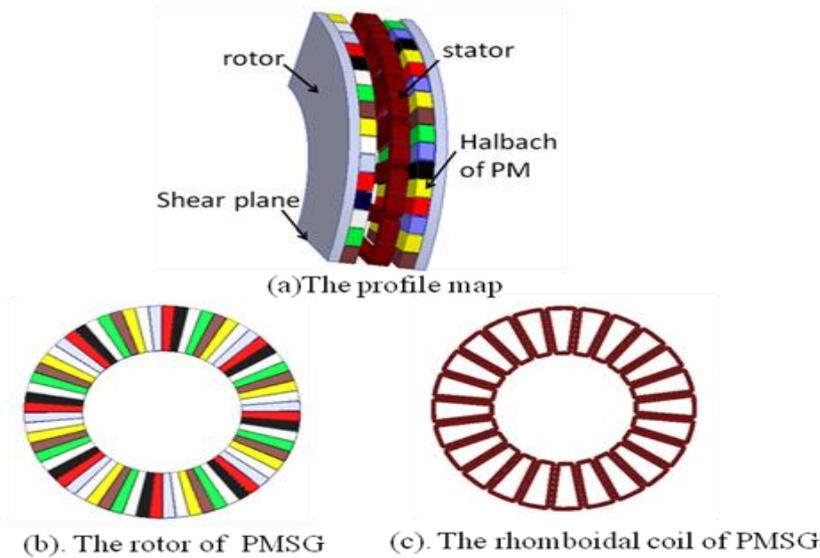


Figure 2. The structure of disc coreless permanent magnet synchronous generator.

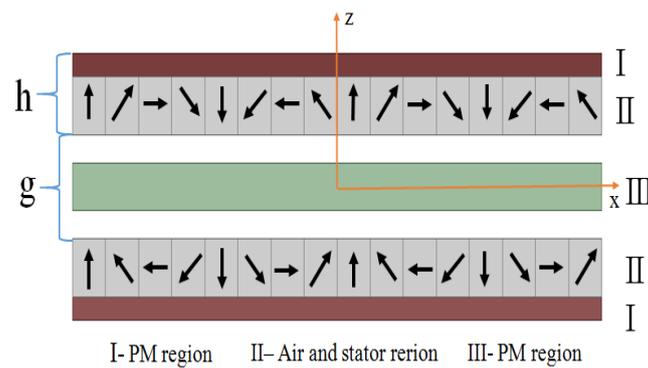


Figure 3. 2D model of AFPM.

The air gap magnetic field of the disc coreless PMSM is generated by the interaction between the permanent magnet region II and the region III, and the formula (8) represents the axial component of the air gap magnetic flux density [15].

$$B_{\delta}(x, z) = B_{\delta} \frac{2}{m_n g} \cosh(m_n z) e^{m_n x} \cos(m_n x) \quad (8)$$

Where B_{δ} describes the air gap magnetic flux density, h is the thickness of the permanent magnet, g is the sum of the equivalent air gap length of the motor which is equal to the length of the air gap and the thickness of the winding. The m_n is calculated by $m_n = (2n-1) \pi / \tau_p$

This machine is a kind of electromagnetic conversion device. It can mutually convert the mechanical energy into electric energy stored as the second power source. The coil cuts the magnetic field lines to produce three-phase voltage. E represents the electromotive force generated by the disc motor.

$$E = \frac{1}{4} \Omega N a_i k_w B_{\delta} (D_0^2 - D_i^2) / a \quad (9)$$

Where D_0 is outer diameter of permanent magnet, D_i is inner diameter of permanent magnet, Ω describes the mechanical angular velocity, and N describes the number of conductors per slot.

The output power is an important parameter for the performance of PMSG. It is affected by the

change of the load, where $\cos\varphi$ is power factor.

$$P = \sqrt{3}UI \cos\varphi \quad (10)$$

2.3. Modeling design

The design of AFPM mainly includes the size of model structure and the choice of material. The model is composed of double-sided rotor and coreless stator. The stator winding consists of many single-layer rhomboidal coils. The windings are fixed together with a composite material of epoxy resin [16]. Figure 2(c) describes the stator model built by the RMxpert in the rapid establishment of the Maxwell 3D.

The rotor has 8 pairs of PMS which are respectively pasted on the rotor yokes. Each pole permanent magnet is composed of 8 sections. The magnetization vector angle of adjacent PM is 45° . The rotor model is established by SolidWorks and then imported into Maxwell 3D. Through the translation and rotation of the stator matching, the geometry model is established. Figure 4 shows the geometry model of PMSG after matching.

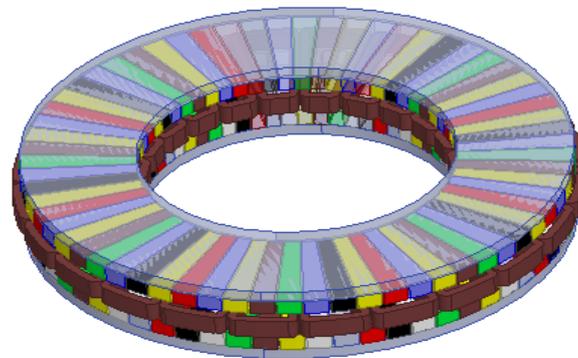


Figure 4. The model of AFPM.

According to table 2, the rotor and stator structures are determined, and all material characteristics have been applied to each component, such as permanent magnets, air-gap, rotors and stator. The double-sided rotor is free to move and the stator is stationary. The materials of rotor select the steel-1008. The permanent magnets used in the generator are NdFeB magnets with $B_r = 1.28$ T, $H_c = 970$ kA/m and $(BH)_{\max} = 310.4$ kJ/m³ and maximum operating temperature of 140°C [17]. In order to increase the distribution of the magnetic flux density in the air gap, the two pairs of poles are distributed by N-S, which is beneficial to the magnetic properties of Halbach array. What's more, compared with 90° , 60° and 45° , the Halbach array permanent magnet is found to be stable at 45° . After selecting the material of the permanent magnet, the magnetization direction of the permanent magnet is specified. It is necessary to establish a local coordinate to define the complex Halbach array permanent magnet.

Table 2. ISG design parameters.

Part	Parameters	Values
Windings	Number of windings	24
	Number of phase	3
	Thickness of coil	13 mm
	Winding type	rhomboidal coil
	Turns per pole	20
	Wire diameter of windings	1.08 mm
Rotor	Outer diameter of PM	320 mm

Inner diameter of PM	185 mm
Number of pole-pairs	8
Thickness of PM	11 mm
Material of PM	NdFe35
Air gap	1 mm

3. Results and analysis

Ansoft Maxwell 3D analysis has two parts, one is static magnetic field analysis, and the other is transient field analysis. The static simulation verifies the rationality of magnetic circuit and the external characteristics are calculated by transient simulation.

As shown in figure 5 is the mesh of disk Coreless PMSG. Figure 6 is the number of the mesh of each part of the generator. It is clearly shown in Maxwell3D when we click the solution data. The maximum mesh size is 39 mm and the minimum is 0.001147 mm. The total number of meshes is 478145.



Figure 5. Mesh generation of rotor.

Total number of elements: 478145

	Num T...	Min edge L...	Max edge L...	RMS edge L...	Min tet v...	Max tet ...
Unnamed_130	24235...	1.50772...	15.7281...	7.64716...	0.006105...	165.005...
Unnamed_129	24145...	1.63336...	14.566...	7.62728...	0.001147...	126.928...
Unnamed_128	1021...	1.79502...	8.23181...	5.62266...	0.024216...	35.1459...
Unnamed_127	933...	1.75442...	8.984	5.70642...	0.228927...	37.5683...
Unnamed_126	806...	2.34069...	9.30841...	6.08912...	0.071451...	42.2206...
Unnamed_125	1091...	2.18254...	8.62349...	5.43598...	0.593198...	26.4447...
Unnamed_124	983...	2.36286...	8.66922...	5.69145...	0.331024...	34.6389...
Unnamed_123	865...	2.94529...	8.43704...	5.83084...	1.09057...	42.4773...
Unnamed_122	997...	2.33532...	9.27686...	5.66973...	0.077068...	38.2952...
Unnamed_121	960...	2.47346...	8.88718...	5.68346...	0.526051...	33.5786...
Unnamed_120	954...	2.39526...	9.02848...	5.7616	0.479451...	31.31...
Unnamed_119	853...	2.16943...	8.97662...	5.94072...	0.322142...	39.0906...
Unnamed_118						

Figure 6. The number of mesh.

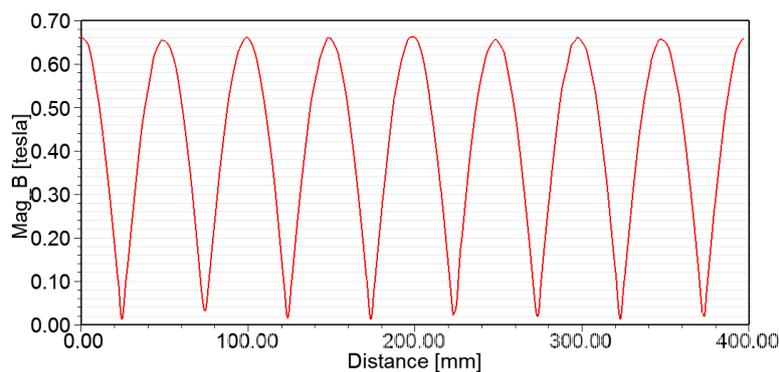


Figure 7. Air gap flux density.

Figure 7 appears the air gap flux density. As expected, the air gap flux density of disc coreless PMSG based on the Halbach is periodical. The peak value is about 0.6626 T. Compared with the value of experience, it is reasonable.

Figure 8 describes the vector distribution of magnetic field intensity. It can be clearly seen the magnetic field direction of each PM. In addition, the intensity of the arrow represents the magnetic field.

Figure 9 shows the magnetic flux density distribution. It can be seen that the magnetic field is enhanced in the air gap, which proves the Halbach array has the ability of gathering magnetic.

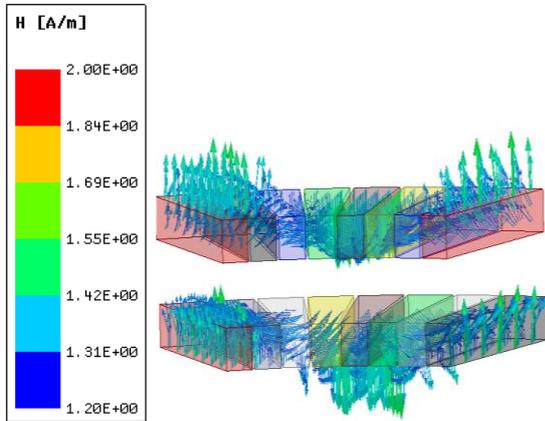


Figure 8. Vector distribution of magnetic field intensity.

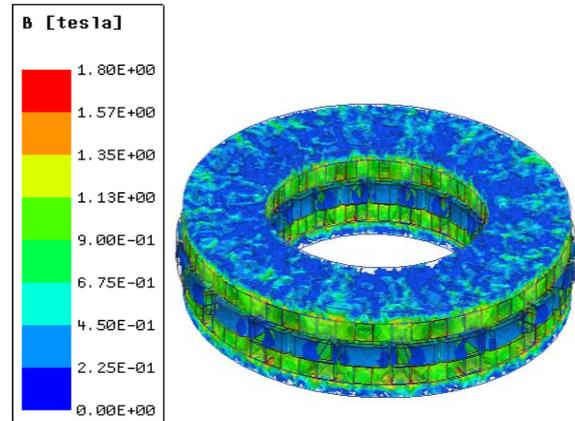


Figure 9. Magnetic flux density distribution of generator.

The Phase voltage presents very perfect sinusoidal characteristics in the figure 10. The amplitude of the voltage is about 335 V.

In this paper, a three-phase load circuit is simulated to analyze the characteristics of PMSG under load condition. The load current is shown in figure 11. The maximum amplitude of the current is 12.5 A.

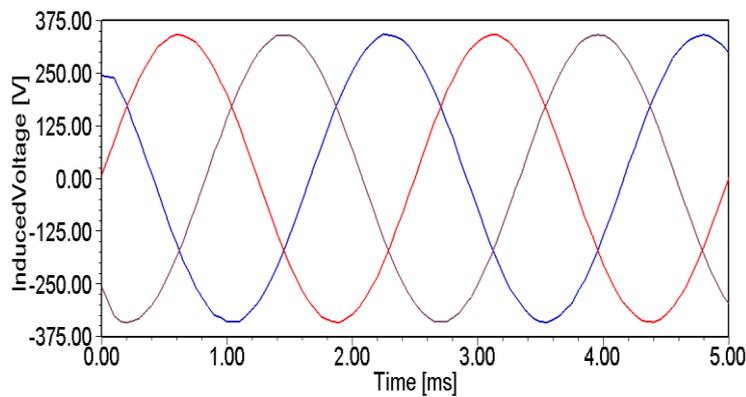


Figure 10. Phase voltage.

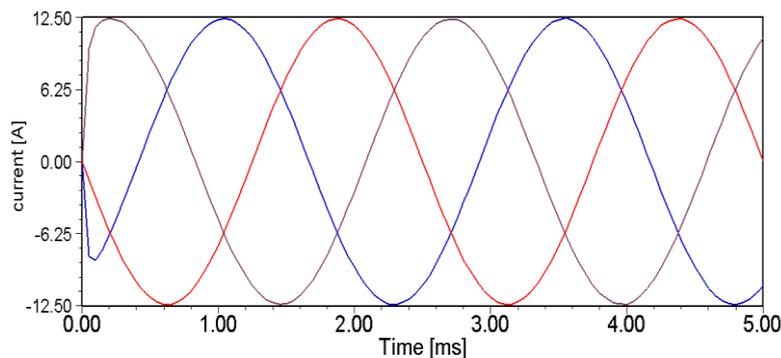


Figure 11. Phase current.

The output power can be obtained from the phase voltage and the current. The rated power factor of PMSG is not a constant value. It is generally less than 1. The generator power factor is 0.9. After calculation, the output power of the generator is 6.53 kW, more than rated power. It is obvious that the generator designed in this paper meets the design requirements. The waveform presents sinusoidal characteristic, which reduces the amplitude of harmonics and vibration and noise of PMSG.

4. Conclusion

The working principles and design features of Halbach permanent magnet disc coreless PMSG are discussed in this paper. Based on the coupled field circuit design of disc coreless PMSG is used in ISG Hybrid electric vehicle. Ansoft Maxwell3D simulated and analyzed the distribution of the magnetic field and the output characteristics. The results show that the disc coreless PMSG with Halbach array-based PM can meet the design requirements, while the PMSG is operating at rated speed, the output power, voltage and current can achieve practical engineering. The field circuit coupling method is used to reduce the design cycle and improve the work efficiency.

They are put forward in order to be further researched:

- The calculation parameters based MCE are not accurate, and the parameters in this paper are verified by simulation.
- The parameter analysis is in the case of ideal values, without considering the effects of loss, so the optimization results have certain limitations.
- The above performance analysis is ready for further prototyping

Acknowledgments

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