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On Performance Analysis of Coreless Permanent Magnet Machine

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Abstract
Coreless Permanent Magnet machines are increasingly used in many industrial applications, such as automotive and aerospace applications, wind turbines, medical equipment, robotics, servo drives, etc. In coreless PMDC machines, the rotor has a coreless winding structure and due to the absence of iron core, the permanent magnet plays significant role in these machines. Also, the shaft's material can change the flux distribution and is another effective parameter on machine performances. Thus in this paper, a typical coreless PMDC brushed machine is simulated and the effects of magnetization direction and the amount of the residual flux density of permanent magnet, and also the influence of ferromagnetic and non-ferromagnetic material of the shaft on machine performances, are studied and analyzed through 3D finite element analysis. The results show that using of ferromagnetic shaft with diametrical magnetized PM can improves the machine performances in motor mode.

Keywords: Coreless Machine, Rhombic Winding, Magnetization Direction, PMDC Machine, Permanent Magnet

Introduction

Due to the increasing needs of industries for high power density, high dynamic and high-efficiency machines, coreless machines have been of interest in recent years. Although the invention of coreless machines goes back to the 1930s, they couldn't be attractive to manufacturers until the late 1960s. As their name suggests, coreless machines have no iron core either for the stator or rotor or both for the stator and rotor structure [1]. Although, they may be completely coreless or they may have rotor back-iron or iron housing to enclose the permanent magnet flux. So, some other terms like "iron-less", "air-cored", "plastic structure [2]" and "non-ferromagnetic disk" have been used for this kind of machines [1]. Of course, researches on the both coreless rotor and stator are very few [1].

The absence of iron core in an electric machine causes several advantages: 1) for coreless rotor configuration, reduction of machine weight and therefore higher dynamic of the motor that leads to low mechanical time constant even less than 10ms and better controllability [3] 2) negligible core losses including eddy current and hysteresis losses. So, it can lead to more power density and efficiency up to 95% [4]. 3) absence of magnetic saturation issues. 4) low inductance due to increasing in flux path reluctance, leads to less arc between brushes and commutator and increase in brush lives. Also, the losses and electromagnetic interferences (EMI) decrease. 5) No cogging torque, torque ripple and axial pull force between stator and rotor [5]- [7].

Beside the advantages, there are some disadvantages for coreless machines too: 1) need for more MMF to create a certain flux through the air gap, and as a result, need for more powerful and higher magnet volume [8] and [9]. 2)weak heat dissipation compared to conventional machines in which the iron core acts like heatsink for the windings. 3) stringent current ripple due to low inductance, make difficulties in drive considerations [9].

The absence of iron core causes the linkage flux decreases. Therefore, it is required to use powerful permanent magnets (PMs) to make enough flux density in air-gap to create sufficient torque and power. it means, almost all coreless machines have PMs in their structure. On the other hand, almost in any kind of machines can be built in coreless structure. But generally coreless machines can be divided into two types: Axial-Flux Coreless PM (AFCPM) machines and Radial-Flux Coreless PM (RFCPM) ones. However, some nascent ideas of hybridization of AFPM and RFPM machines is presented in recent years to achieve more power and torque density [10]and [11]. Due to the disk-type shape, high compactness and light mass of the AFCPM machine, it has been used in many applications such as hydro energy power generation [12], automotive application [13], propulsion of vehicle like EVs and aircrafts [14], flywheel energy storage systems [15] and wind turbines [16]. RFCPM machines are more suitable for high-speed applications compared to their axial-flux counterparts [17] and they are quite compatible with servo industrial drives [16], various hand-help battery-operated devices, medical equipment¸ ATM cash dispensers, robotics¸ laser leveling system drives, and aviation and space applications [3].

AFCPM machines have attracted more attentions and there are lots of researches on their optimal design and performance analysis [11]-[15]. In [18] genetic algorithm is used to improve the performance of the AFCPM machine. In [19] a multi-objective optimization is proposed for design of a multidisc coreless AFPM machine through combination of response surface method (RSM) and genetic algorithm (GA) which improves the torque ripple. In [20], the PM shape impacts on a back emf waveform and torque ripple of an AFCPM have been investigated and demonstrated that sector-like magnets and then square magnets, lead to good results. Also, Halbach array PM arrangements have been widely studied and used to improve the quality and sinusoidal level of air-gap flux density in coreless machines [4]and [21].

One of the novelties presented for coreless windings is using flexible PCB, instead of copper wires. Using PCB has advantages like coil accuracy, design flexibility and manufacturing process reliability [14]. For example, in [22] a new topology of flexible PCB winding is proposed and shown that it can make higher copper filling factor, better heat dissipation, and reduction of phase resistance that causes a great improvement of the machine performance in comparison with other topologies [14]and [22]. Also in [23] the 3D printing technology is applied to improve the output power and efficiency of a collaborative robot. In [15] a novel coreless multi-phase magnetic resonant motor (MMRM) with analytical design has been presented where the stator and rotor are 3-D printed by reinforced plastic fibers. However, the stator coreless winding in AFPM machines are mostly trapezoidal shape coils which can lead to better winding factor compared to circular and rhomboidal coils [4]. For example, in [4] a novel composite structure on trapezoidal coils using wedge-shape effective conductors is proposed which reduces the eddy current and DC copper losses and improve the output characteristics.

It is noteworthy that in high-speed machines, the eddy current losses become a significant issue and it may cause PM demagnetization due to overheating [24]. Many researches have considered this problem and proposed calculation of eddy current losses in coreless PM machines [24]and [25]. For example, in [26] a 3D model of armature reaction filed of helical winding is presented with considering rotor eddy current losses.

The coreless AFPM machines mostly are synchronous or BLDC machines with a 3-phase coreless or slot-less stator winding and a few researches have been done on rotor coreless windings. In [27], a comparison between Rhombic and concentrated winding has been done in a slot-less RFPM BLDC motor and it’s shown that the torque ripple with rhombic winding is less than that of the other one. Also, in [25] a 3-D modeling approach was proposed for 3 different kinds of skewed slot-less or air-gap windings such as skewed, rhombic and hexagonal for a 3phase cylindrical machine, to calculate the electromagnetic fields and modeling the armature reaction felid considering PM eddy-current losses. Authors of [28] discussed about two semi-analytical and numerical methods that evaluating the geometry quickly to calculate the tangential torque of rhombic winding in a high-speed PM machine. In addition, in [24], an analytical approach for 3-D modeling and calculating the magnetic field caused by helical winding is presented.

Based on the best knowledge of the authors, the coreless rotor winding has been rarely studied. Furthermore, coreless radial-flux PM machines, especially on cylindrical brushed DC types are less considered in literature. Therefore, in this paper, the focus is on coreless RFPM brushed DC machine, and the influence of PM material, the charring direction of the PM, the employed material for the shaft the on performance of a typical machine is studied by 3D time stepping finite element analysis.

The Studied Machine

One of the most applicative types of coreless machines, is the brushed DC coreless machine. Due to the simplicity and lightness of its structure, this machine has numerous applications in many industries such as medical equipment (X-ray machines, laboratory equipment, prosthetics and small pumps), domestic, vibrators and banking and office automation (ATMs) [3]. Also, because of high dynamic of the rotor, they are used in sensitive robotic applications [3].

The structure of a typical coreless brushed DC machine is shown in Fig. 1. The length and the outer diameter of the machine is 100mm and 50mm, respectively. The nominal voltage and terminal resistance of the studied motor is 24 V, and 103 mΩ, respectively.

The stator includes the fixed 2-pole sinusoidally magnetized PM in the middle with the motor iron housing guiding the magnetic flux. Also, the rotor is made of a rhombic shape winding with a self-supporting structure and 15 rhombic coils which are wound in form of lap (spiral) winding. It is worth mentioning that in a coreless machine, unlike conventional electric machines, there is no iron core for windings to be wound around it. Therefore, the winding must have a self-supporting structure or it can have a non-ferromagnetic core like plastic or fiber carbon. The coreless winding with no core must be covered by epoxy resin, to guarantee enough winding strength at high speeds. Such an air-gap winding is used in low-power, high-speed machines mainly for two reasons: first the absence of cogging torque and losses resulting from slotting and second low-cost manufacturing for small-sized slot less or coreless PM machines compared to slotted ones. However, the less magnetic loading of coreless machines results in higher copper losses [28].

The brushes and commutator can be made of precious metal for small current and voltages due to their low contact resistance. For higher currents and powers, the graphite-copper brushes and copper alloy commutator are better suited and they are less sensitive to brush fires which are inevitable.

for creating enough magnetic flux in the coreless machines, high-power permanent magnets are used. The rare-earth Neodymium-Iron-Boron magnets are suitable choices due to their good accessibility and high energy. Therefore, the amount of flux density and the magnetization direction of magnets, are effective parameters in coreless machines. In the current design, a NdFe30 permanent magnet with the residual flux density (B_r) of 0.5 Tesla is employed.

The shaft and the stator are made of ferromagnetic materials. In the studied machine, CK-45 steel is used for stator housing and the effects of the ferromagnetic or non-ferromagnetic shaft’s material on the machine

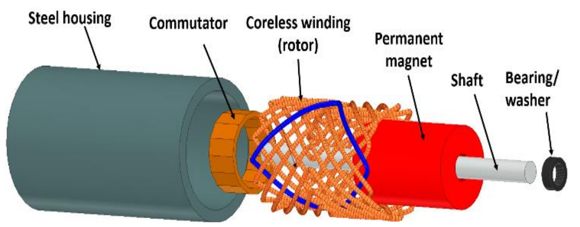


Fig. 1. Structure of a typical coreless PMDC machine

performance is discussed.

3D Finite Element Analysis

Ansys Electronics Desktop 2022R2 is used for the simulation. The schematic of the mesh on the studied machine is shown in Fig. 2. The total number of mesh elements are 273400.

The performance of the machine is discussed in motor and generator mode and the influence of the PM's charging direction and the residual flux density, as well as the employed shaft material is studied. It is worth mentioning that for each simulation, only one parameter is changed and the others are kept in nominal conditions to clarify the influence of the variable factor. For the amplitude of residual flux density of the permanent magnet, B_r, 0.4, 0.5 and 0.6 T are examined and for the magnetization direction, the radial and diametrical magnetization are applied to the PM. Fig. 3 shows the distribution of the magnetic flux density on the studied machine with two studied magnetization directions.

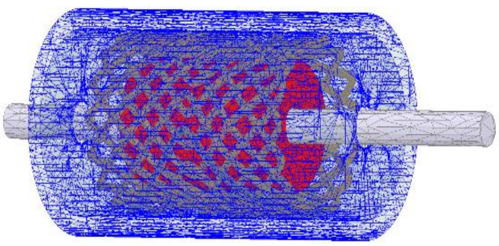
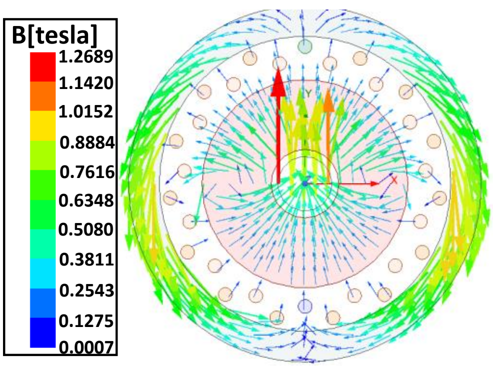
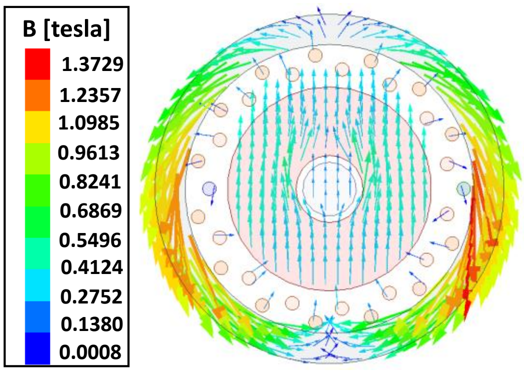


Fig. 2. The schematic of the mesh on the studied motor



(a)



(b)

Fig. 3. Cross section of machine; The distribution of the magnetic flux density on the studied machine: (a) using radial magnetization of the PM, and (b) using diametrical magnetization of the PM

A. Motor Mode

A 405 mNm load torque is considered as the full-load torque in motor condition corresponding to nominal speed. Repeating the simulations for diametrical and radial magnetization of the PM, as shown in Fig. 4, shows the first can make more flux linkage without changing in wave form and thus, higher amplitude of induced electromagnetic force (emf) in coils.

Other performance characteristics of the studied machine considering radial/diametrical magnetization of the PM are summarized in Table I.

Also, the non-ferromagnetic shaft caused reduction in flux linkage and thus in the induced voltage (emf) specially due to increase in air-gap reluctance of flux path in the middle of the PM. Therefore, as the torque is proportional directly to the magnetic flux in a PMDC machine, for a certain amount of torque in motor mode, it drains more current to generate the desired torque. The performance indices of the motor considering the shaft material are given in Table II.

To study the influence of the B_r, the ferromagnetic shaft and radially magnetized PM are considered. The results show that by increasing the PM's residual flux density, the current and torque ripple decrease. Also, it shows that in spite of reduction in output power by increasing in B_r, the efficiency improves. The electromagnetic torque of the studied machine considering different values for B_r are

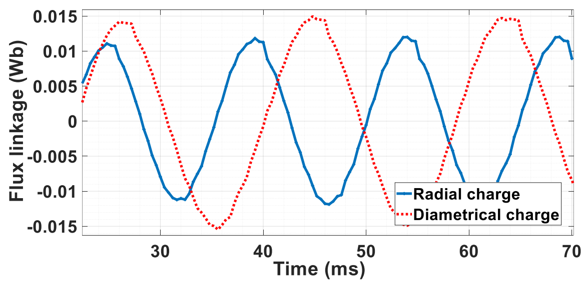


Fig. 4. The influence of using radial/diametrical magnetization of the PM.

Table I. The influence of using radial/diametrical magnetization of the PM, considering nominal load (I: current, N: nominal speed, T_{ripple}: torque ripple, η: efficiency, and P_{out}: output power)

Magnetization direction	I (A)	N (rpm)	T_{ripple} (%)	η (%)	P_{out} (W)
Diametrical	6.77	3230	1.23	84.31	137
Radial	9.1	4050	1.97	78.66	171.8

Table II. The influence of using ferromagnetic/non-ferromagnetic material for the shaft, considering nominal load

Shaft material	I (A)	N (rpm)	T_{ripple} (%)	η (%)	P_{out} (W)
non-ferromagnetic	10.6	4580	4.93	76.35	194.24
ferromagnetic	9.1	4050	1.97	78.66	171.8

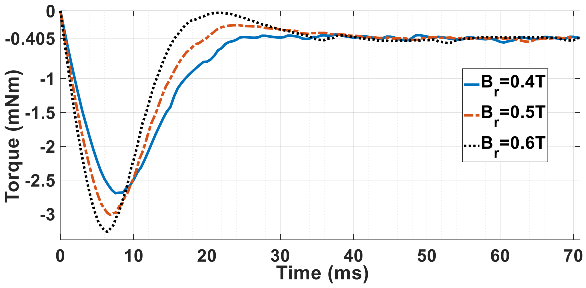


Fig. 5. The electromagnetic torque of the studied machine considering different values for B_r

Table IV. The influence of using different values for B_r, considering nominal load

B_r (T)	I (A)	N (rpm)	T_{ripple} (%)	η (%)	P_{out} (W)
0.4	11.1	4567	8.1	72.7	193.7
0.5	9.1	4050	1.97	78.66	171.8
0.6	7.5	3520	1.48	82.9	149.28

given in Fig. 5 and the other performance indices are summarized in Table IV.

B. Generator Mode

In generator mode the rotor is rotated using the nominal speed and the output voltages in no-load and full-load condition (2.12 Ω resistive load) are calculated. The influence of different values for the B_r, are given in Table V. Also, the output voltage of the machine considering different values of B_r, is presented in Fig. 6. It can be seen from Fig. 6 that by increasing B_r, in spite of increasing in output voltage, the voltage ripple increases unlike torque ripple in motor mode.

The influence of the magnetization direction is also studied in the generator mode and the results are given in Table VI.

And finally, the influence of the shaft material in generator mode is presented in Table VII. As it can be seen from Table VII, using non-ferromagnetic shaft leads to increase in magnetic flux path reluctance and thus

Table V. The influence of using different values for B_r, in generator mode

B_r (T)	No-load	Full-load	
	Output voltage(V)	Output voltage(V)	Current(A)
0.4	19.4	15.6	7.4
0.5	24.2	19.8	9.35
0.6	28.9	24	11.3

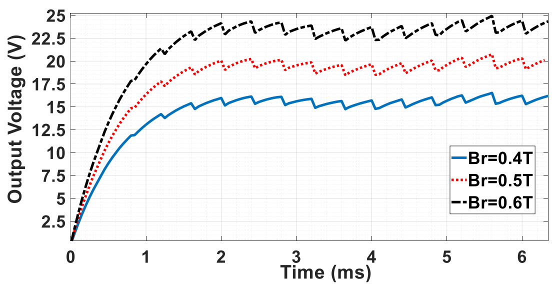


Fig. 6. The output voltage of the machine considering different values of B_r with R_{load}=2.12 Ω

Table VI. The influence of magnetization direction, in generator mode

Magnetization direction	No-load	2.12 Ω resistive load	
	Output voltage(V)	Output voltage(V)	Current (A)
diametrical	32.7	26.4	12.4
radial	24.2	19.8	9.35

Table VII. The influence of shaft material, in generator mode

Shaft material	No-load	2.12 Ω resistive load	
	Output voltage(V)	Output voltage(V)	Current (A)
Non-ferromagnetic	19.5	16.7	7.88
ferromagnetic	24.2	19.8	9.35

reduction in flux and induced voltage and output power. The results show that using ferromagnetic shaft or diametrical charged PM can lead to less current and torque ripple in motor mode with the same load and more output voltage in generator mode. Therefore, it seems that simultaneous use of ferromagnetic shaft and diametrical magnetized PM with maximum amount of B_r, improves the machine performance especially in motor mode.

Conculosion

In this paper, a typical coreless brushed PMDC machine was simulated and the effects of the ferromagnetic and non-ferromagnetic material of shaft, the radial and diametrical magnetization of PM and different amount of B_r were analyzed and discussed in motor mode and generator mode. it was shown that by using either ferromagnetic shaft or diametrical magnetized PM, in spite of reduction in output power, the flux linkage increases and the current and torque ripple decrease in motor mode. Also increasing in amount of permanent magnet B_r leads to same results for motor mode. The results also showed that in generator mode increasing in flux linkage happened in the same ways as in motor mode and led to more output voltage but with more voltage ripple.

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