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Optimal Design and Analysis of Conical Magnetic Gear

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ABSTRACT: Conical machines with a unique conical rotor and stator design have several advantages over electrical machines with traditional designs. The conical shape allows for greater torque and efficiency, which makes these machines ideal for use in heavy machinery and industrial equipment. Besides, their compactness in comparison with traditional machines makes them easier to integrate into manufacturing processes. Furthermore, since magnetic gears (MGs) have provided a solution to overcoming mechanical challenges and disadvantages of mechanical gears, their development has become a hot research topic in the last few years. Due to asymmetric geometry and special flux paths, the analysis should be modeled in 3-D finite element tools. In this paper, a hybrid structure, named conical MG, is introduced in order to benefit simultaneously from the advantages of radial flux and axial flux structures of MG. This topology can provide more contact surface of permanent magnets (PMs) and, thus, increase the torque density, with a proper design and the optimization of dimensions. The proper shaping of the PMs and providing the correct structure of MG can lead to a high impact on the output characteristics of the system. This design improves the transmission torque by forming the magnetic fields in air gaps. To compare the proposed topology, the optimal design of the model is compared with the conventional radial flux structure using the genetic algorithm and 3-D finite element method to obtain maximum torque density. The results are compared and the superiority of the proposed model is proved.

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1- Introduction

Recently, in many industrial applications, gears have been used as an intermediate of prime mover and load. A gear is a device used to change the speed, torque, axis, or direction of rotation. Conventional mechanical gears are associated with problems such as friction, wear, noise, the need for lubrication, and the possibility of breaking and crushing under overload conditions. To overcome these problems, a new structure, called magnetic gear (MG), has been introduced. Because of the use of magnetic fields and magnetic forces instead of physical contact of gears, these gears neither require lubrication not break or crash; hence, they show inherent overload protection.

MGs have been introduced in different structures of radial flux, axial flux, or linear, each of which has its characteristics and disadvantages depending on geometry and dimensions.

Most of the existing literature on magnetic gears focuses on the radial flux coaxial magnetic gear shown with surface-mounted permanent magnets (PMs) in Fig. 1(a). However, the axial dual of this topology, shown in Fig. 1(b) has also received some attention [1]. Coaxial magnetic gears consist of two rotors with PMs and another middle rotor with magnetically soft poles called modulators. In an axial-flux MG two rotors at the two sides of the airgap interact by the magnetic flux flowing axially across the ferromagnetic segments. It is particularly suitable for applications that require a flat outside shape and hermetic isolation between the input and output shafts [2]. Although the fundamental operating principles of both topologies are similar, there are some important design, performance, and scaling differences. For radial flux gears, the radial magnetic forces on each rotor can be canceled out with symmetry. Alternatively, in axial flux gears, symmetry cancels out the off-axis torques, but there are still unbalanced net axial magnetic forces on the rotors [3]. Different types of MGs are compared by output performances as static torque (two rotors are kept stationary, and a rotor rotates to produce a sinusoidal torque named static torque), dynamic torque (a rotor is kept stationary, and two rotors rotate according to gear ratio to produce an average torque with fluctuations), average torque (the average of dynamic torque or magnitude of static torque), and cogging torque(the range of dynamic torque fluctuations).

In order For MGs to compete with mechanical gears, all types of structures and studies are trying to increase their torque density, reduce cogging torque, and create economic efficiency [4-6]. In [7], a new structure has been investigated

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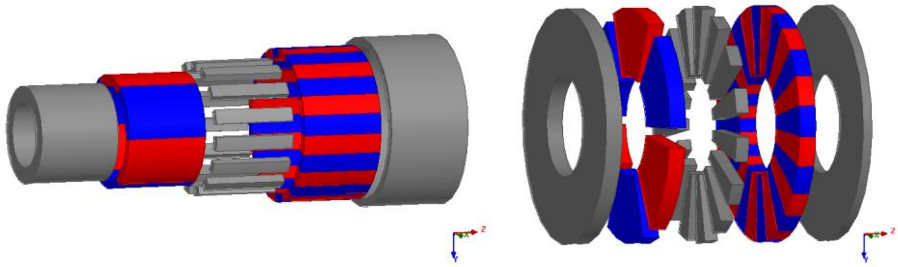


(a) (b)

Fig. 1. Exploded view of MGs topology (a): radial flux (b): axial flux

to improve torque density. In this structure, the method of pulse width modulation and pole face shaping has been used to improve magnetic field distribution. In [8], a superconducting modulator is presented to improve the torque density by improving the field modulation performance and reducing the leakage flux. In [9], a new structure with the name of arcuate double-layer MG is introduced using the combination of two structures of radial flux and axial flux to increase torque density by using all the flux capacities of the structure in all dimensions.

In [10], torque density has been increased by changing the placement of PMs as a concentrated flux topology. In [11], a higher torque density has been extracted by using a magnetized superconductor instead of PMs. The radial flux structure with the possibility of increasing axial length, and axial flux structure with the possibility of increasing the effective radius can provide advantages according to their specific applications. In [1] both of the mentioned structures have been investigated in terms of volumetric torque density and mass torque density of the PMs. The results have shown that both structures provide similar performances in high transmission torque and low gear ratio. The sensitivity of the volumetric torque density to changes in the radius is more severe in the axial flux structure. In radial flux structure, the balance of the radial forces acting on the internal rotor can be ignored; however, in axial flux structure, significant axial forces are applied to the rotor, which also requires special mechanical considerations. In [2], different structures of radial flux and axial flux are compared, and the superiority of radial flux structure in the transmission torque density and dependence of the proposed structure on the type of application has been discussed.

To benefit from the advantages of radial flux and axial flux structures, conical structures are suggested. In [12] a conical rotor permanent magnet synchronous motor has been investigated. It is shown that the air gap magnetic field is linearly reduced and the torque decreases with an increase in the axial displacement of the rotor. However, it is still quite challenging to derive the expression of axial force with respect to *d*-axis current and cone angle. [13] shows an innovative application of a conical-shaped motor for an aerospace traction application. The motor could provide a solution for avoiding active clutch mechanisms in applications where engagement/disengagement is required. [14] presents a novel structure of a permanent magnet synchronous motor with a conical rotor and studies its flux-weakening performance in detail. Instead of changing the current angle, a decrease in flux linkage can be achieved by moving the conical rotor in the axial direction.

In this paper, to maximize torque density and make maximum use of the available space to place the PMs (as the magnetomotive force MMF of the magnetic circuit of the MG), a conical structure is introduced as a combination of axial and radial flux structures. As shown in Fig. 2, three different rotors of a MG are placed in a conical shape, which increases the effective length of the PMs. The main approach to the improvement of torque and power density is the maximization of the air gap surface in a MG volume. For coaxial MGs, this is possible by the implementation of conical rotor designs. Theoretical limitations in the case of conical and multistage rotor usage have been considered. Optimal cone angle has effects on maximum torque density.

2- Principles of Operation

The MGs have an inner and outer rotor with a PM and a middle rotor with separate soft magnetic parts called modulators (Fig. 3). The magnetic flux produced by PMs is modulated by passing through the modulator pieces and creates flux harmonics with a different number of poles and various rotational speed. By coupling the third rotor with the strongest generated flux harmonic (different from the main harmonic), it is possible to create the effect of gearbox i.e., power transmission with a different speed and torque.

By expressing the radial and tangential components of the magnetic field as a function of the radius (r) and rotor angle (ϕ) [15, 16], by taking into account the dimensions and the number of poles of the rotors (p_i is the number of internal rotor pole pairs; ω_i is the rotational speed of internal rotor;

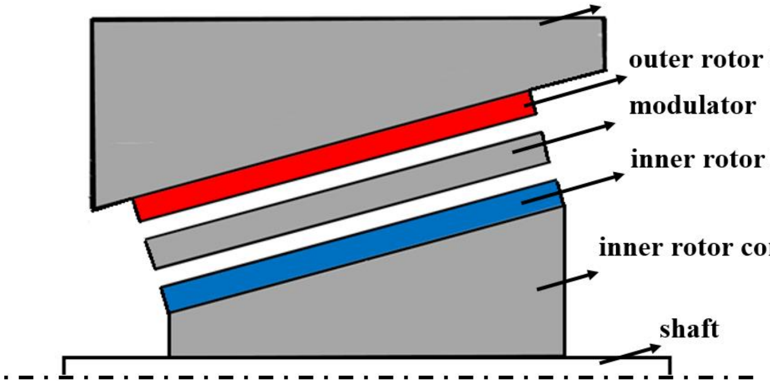


Fig. 2. Axial section of conical MG topology

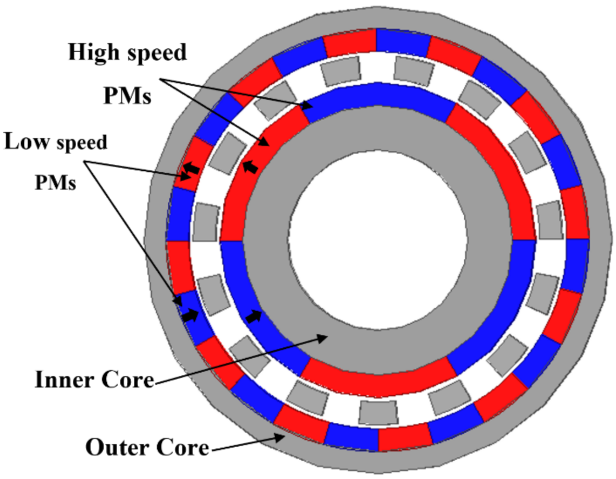


Fig. 3. Different parts of conventional radial flux MG

θ_{i0} is the initial angle of internal rotor; ω_s is the rotational speed of modulators; and n_s is the number of modulators), and by multiplication in the magnetic permeance distribution function, the distribution of the magnetic field can be extracted in terms of harmonic components. The strongest harmonic (the highest magnitude) can be selected for coupling with the third rotor. In this condition, the number of pole pairs of air gap magnetic field harmonics can be stated as [4-6]:

$$P_{m,k}=\left|mp_i+kn_s\right| \quad m=1,3,\ldots,\infty\ ;k=0,\pm1,\pm2,\pm3,\ldots,\pm\infty \tag{1}$$

In addition, the rotational speed of the pole pairs resulting from the mentioned harmonics can be stated as [4-6]:

$$\omega_{m,k}=\frac{mp_i}{mp_i+kn_s}\omega_i+\frac{kn_s}{mp_i+kn_s}\omega_s \tag{2}$$

To engage the external rotor at the same time with the strongest produced harmonic, the combination of *(m=1, k=-1)* should be selected. In this way, the relationship between the number of pole pairs of the external rotor (p_o) and the internal rotor (p_i) with the number of modulators (n_s) will be as:

Table 1. Dimensions and specifications of the studied MG

Variable	Symbol	Value	Material
Inner rotor pole pair	P_h	3	NdFeB-N40
Outer rotor pole pair	P_l	12	NdFeB-N40
modulators	n_s	15	M6
Inner rotor inner radius	R_{in}	15 (mm)	M400-50A
Inner rotor outer radius	R_o	50 (mm)	M400-50A
Air gap length	l_g	1 (mm)	-
Modulator radial thickness	Th_m	6 (mm)	-
Outer PM radial thickness	Th_{opm}	5 (mm)	-
Outer core radial thickness	Th_{oc}	15 (mm)	M400-50A
Modulator arc to modulator pitch ratio	τ_m/τ_M	1	-
PM flux density residual	B_r	1.22 (T)	-
Special electrical resistance	ρ_s	45 ($\mu\Omega cm$)	-
Axial length of MG	L	50 (mm)	-
Minimum length of bridges	Th_q	1 (mm)	-
Inner rotor pole pitch	α_p	60 (deg)	-
Inner rotor PM length	PM_w	40 (mm)	-
Inner rotor PM width	PM_h	6 (mm)	-

$$n_s=p_i+p_o \quad (3)$$

Finally, considering the above equations, the relationship between the rotational speed of the inner rotor (ω_i), the middle rotor (ω_s), and the outer rotor (ω_o) will be explained as [4-6]:

$$\omega_o=\frac{p_i}{p_i\text{-}n_s}\omega_i\text{-}\frac{n_s}{p_i\text{-}n_s}\omega_s \quad (4)$$

By assuming the external rotor as a stationary one ($\omega_o=0$), the gear ratio (G_r) can be calculated as:

$$0=\frac{p_i}{p_i\text{-}n_s}\omega_i\text{-}\frac{n_s}{p_i\text{-}n_s}\omega_s\rightarrow G_r=\frac{\omega_i}{\omega_s}=\frac{\text{-}n_s}{p_o\text{-}n_s}=\frac{n_s}{p_i} \quad (5)$$

The dimensions of the base case conventional radial flux MG (Fig. 2) are presented in Table 1. Due to the focus of this article on the structure of the proposed rotor, the main dimensions of the middle rotor (modulators), and the outer rotor are assumed to be constant, and the gear ratio and the radius of the inner rotor are considered to be the same in different studies to allow a fair comparison.

3- Proposed Conical MG Structure

Conical structures in electrical machines are commonly used with the aim of controlling the air gap length, resulting from the axial movement of the internal rotor, and of controlling the field and the output characteristics of the machine. In this paper, in addition to the above-mentioned points, the main purpose of creating and investigating the conical structure is to increase the effective surface of the PMs to increase the torque density of the MG. Therefore, according to Fig. 4, the geometry design of the topology has been started with the definition of design variables with a focus on the conical structure and the cone angle.

In different studies, torque density is used as an objective function in optimization. Due to the presence of parts such as core, shaft, and bearings in the final structure and their significant price differences with effective materials such as permanent PMs, redefinition of the objective function is required. Therefore, the ratio of torque to the volume of the PMs is determined as an objective function. The effective surface of the PMs, equivalent to the surface of the air gap, has a direct effect on the produced MMF. In addition, its increase can be optimized by the assumption that the total volume of the system remains constant.

In the first step, in a fixed volume, an effort was made

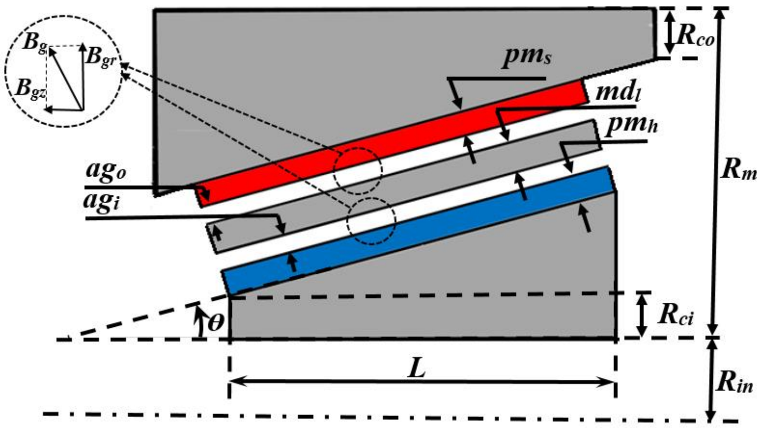


Fig. 4. Optimization variables of conical MG

to maximize the ratio of the effective area of the air gap. For the initial understanding of the subject, according to the dimensions and geometry of Fig. 3, a cylinder was assumed with an inner diameter of D ($R_{in}=D/2$) and a thickness of R_m. By changing the cone angle (θ), the axial length of the conical rotor will change between 0 and L. Increasing the cone angle will decrease the axial length and increase the effective radius (R_m). To optimally determine the effective length and radius, the ratio of the conical surface to the cylindrical surface as well as the ratio of radius to length was determined and optimized for different conical angles. As stated in [17], the maximum ratio of the surface of the PM was obtained at $\theta=45^0$ and the ratio $R_m/L=1$. It is obvious that by creating fractures in the arrangement of PMs, the surface ratio can be increased, but it leads to many challenges in construction. According to what was mentioned above, with the ratio of the effective radius to the length as equal to 1, optimization with the variables stated in Fig. 4 will be done using 3-D finite element method (FEM) and a genetic algorithm (GA); optimization module using objective function (O.F.) as:

$$O.F. = \frac{T_d}{V_{PM}} \quad (6)$$

In this paper, an intelligent GA is applied. GA has three operation factors namely reproduction, crossover, and mutation. Relatively, higher average torque and lower torque ripple values are pursued as the main objectives of optimization. Optimization is processed with the following considerations: a population of 100 elements; a maximum generation number of 35; a crossover probability of 0.7, and a mutation probability of 0.1. To quantitatively compare the electromagnetic performances of the proposed conical MG, different parts are optimally designed by using the FEM-GA coupled method. Maxwell package is used to build the parameterized FE model of the conical MG. The objective of the optimization is to achieve the highest output torque density with the lowest level of PM consumption. When the dimensions are given, by rotating the rotor slowly, an alternative torque versus rotor position can be obtained. The maximum torque and PN volume are used to calculate the O.F. According to the above equation, maximizing volumetric torque density (T_d) and minimizing the volume of the PMs (V_{PM}), as the main costly part of the structure, are the main optimization goals.

4- Simulation Results

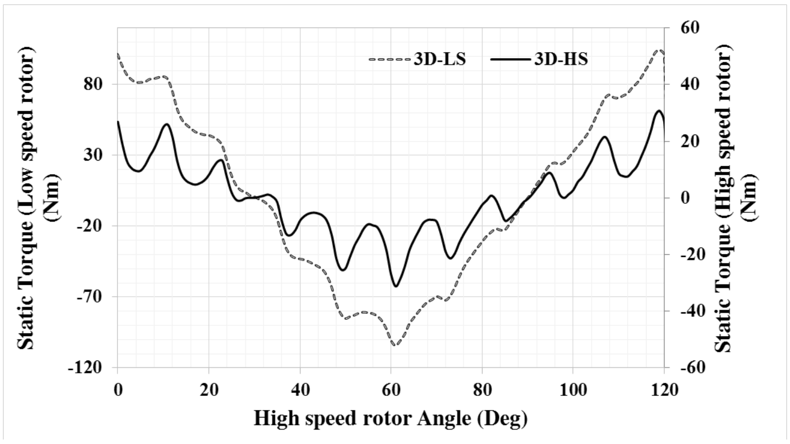
Maxwell software provides an initial mesh based on "surface approximation settings". If needed, the software will improve the condition of the mesh and make it more accurate in the more sensitive areas. Initial meshing is possible by the user. In most cases, the software uses the Ansoft TAU Mesh feature for meshing with proper accuracy, speed, quality, and reliability compared with the Ansoft Classic Mesh option. Meshing is improved by the iterative improvement method in sensitive points with high error density.

Table 2 shows the results of the conical MG optimization. The inner rotor and modulator torque as high-speed and low-speed rotor angles are shown in Fig. 5. Fig. 5(a) illustrates the static torque, and Fig. 5 (b) depicts the dynamic torque of the rotors.

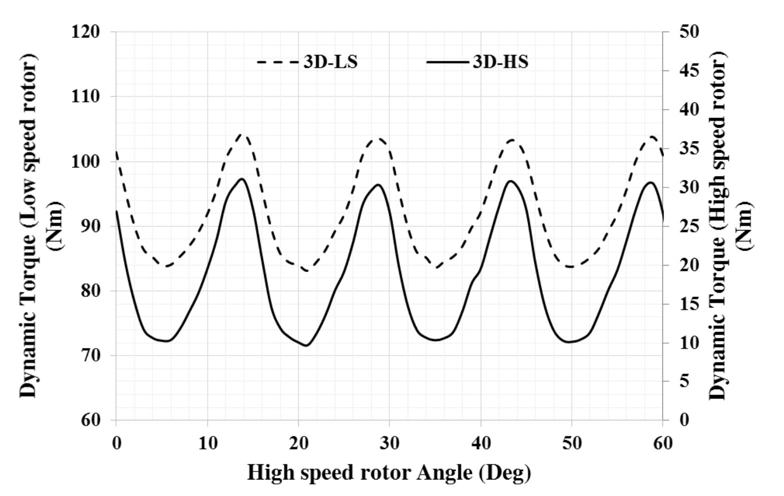
The average torque and cogging torque percentage are presented in Table 3. The difference between the optimization results with optimized conventional radial flux structure (without coning) is compared. The superiority of the proposed structure in providing 11% more torque density indicates the

Table 2. Optimization results of conical MG

Variable	Symbol	Value
Total MG radius	R_m	95 (mm)
Shaft radius	R_{in}	15 (mm)
MG Axial length	L	50 (mm)
Cone angle	θ	43 (deg)
Inner core inner radius	R_{ci}	50 (mm)
Outer core inner radius	R_{co}	70 (mm)
Outer air gap length	ag_o	1 (mm)
Inner air gap length	ag_i	1 (mm)
Outer PM radial length	pm_s	5 (mm)
Inner PM radial length	pm_h	5 (mm)
Modulator radial length	md_l	6 (mm)



(a)



(b)

Fig. 5. 3-D FEM modeling torque of the optimal conical MG (a): static torque (b): dynamic torque

Table 2. Comparison of conical and radial optimization results

	Cogging torque (%)		Average torque (*Nm*)	
	HS	*LS*	*HS*	*LS*
Optimized Radial flux MG	76	15	17	85
Optimized conical MG	103	21	19	95

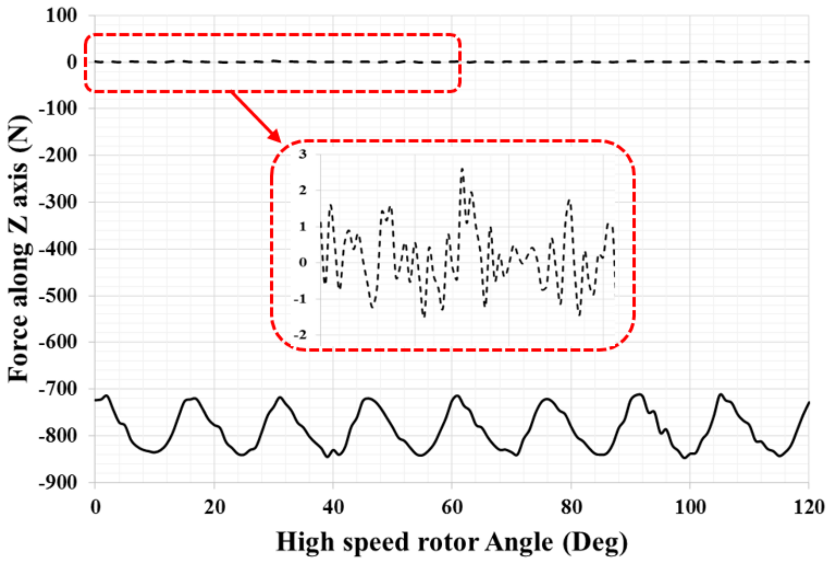


Fig. 6. Axial force on the inner optimized conical rotor

superiority of the conical structure. Results show that conical MG is associated with higher cogging torque, although it has not been the goal of this paper; nevertheless, its percentage can be reduced by using skewing methods.

The axial forces, applied on the inner and modulator rotors, are shown in Fig. 6. Due to the asymmetric structure of the conical rotors, the axial forces during the rotation of the rotor can challenge the accurate operation of the MG. Therefore, mechanical considerations will be unavoidable, especially in selecting roller bearings instead of ball bearings.

Fig. 7 shows the magnetic field distribution in different components of the optimized conical MG. At sharp points and edges, due to the flux concentration, momentarily saturation can occur, which will change in the next moments due to the rotation of the rotor. A wrong rotor design may lead to a decrease in the average torque and a very high torque ripple. The peak-to-peak ripple can even reach a high value if the rotor or modulators are incorrectly designed or saturated. Since the ferromagnetic modulators are connected to the middle rotor, a part of flux, excited by PMs, enters the ferromagnetic modulators, which increases the saturation of the modulators.

5- Conclusion

In this paper, a new design of conical shaping in MG structure was presented to improve torque transmission as well as to make use of the advantages of the conventional radial and axial flux structures to create a higher contact surface between rotors. In the proposed model, by an appropriate definition of the cone angle and the dimensions of the effective components in the output performance characteristics, the magnetic flux density of the rotor pole was distributed in the air gap to obtain maximum transmission torque. The optimization results of the conical MG were compared with the optimal, conventional, radial flux MG, and the superiority of the proposed model in providing a more optimal O.F. was proved. The average torque was improved from 85 *N.m* in the base initial model to 95 *N.m* in an optimal conical design. Although both topologies can reduce the cogging torque to the desired level, conical shaping creates a larger cogging torque due to the vaster contact surface between the rotors.

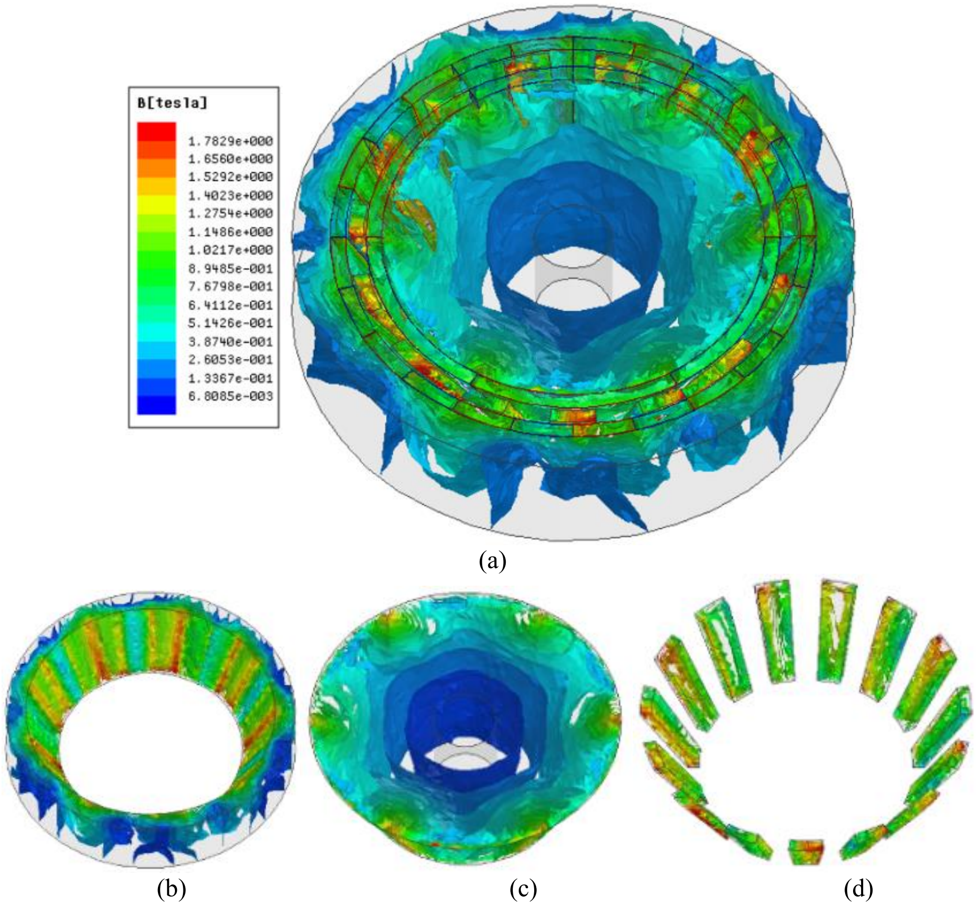


Fig. 7. 3-D flux density distribution in different parts of optimized conical MG (a): total conical MG (b): modulators (c): inner core (d): outer core

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