Field Analysis on Magnetic Transmission Mechanism of Downhole Turbine Generator

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Abstract: New downhole turbine generator can transmit the high speed rotation of the turbine to the rotor of the generator without contact by magnetic transmission mechanism to provide continuous power. Driving torque on magnetic transmission mechanism is a key parameter. This paper mainly studies the field on magnetic transmission mechanism of downhole turbine generator by using ANSYS software. The effects of thickness of permanent magnets, thickness of distance sleeve, the average radius of working field, air gaps and rotating speed on torque were quantitatively analyzed, and eddy current in distance sleeve with different structure parameters was also analyzed. Through the analysis, it can be shown that the influence of the eddy current in distance sleeve should be considered when designing the transmission mechanism to avoid reducing large torque. The size of magnetic transmission mechanism should be optimized for the design goal of large torque and low eddy current, avoiding overheating and making sure that the generator works normally.

Keywords: Turbine generator, magnetic transmission, magnetic field, magnetic torque, eddy current, downhole.

1. INTRODUCTION

Downhole turbine generator is the indispensable source power for rotary steering drilling system and automatic vertical drilling system. It provides power for the corresponding system to measure, store and transmit the downhole information, and it is also the source power for the control function of the system. The dynamic seal of traditional downhole turbine generator is not reliable and there is a serious risk of erosion damage. New downhole turbine generator can transmit the high speed rotating of the turbine to the rotor of the generator, without contact, by magnetic transmission mechanism, achieving complete isolation of the generator from the fluid mud, and improving the working environment of the turbine generator.

Presently, the study on magnetic transmission mechanism is still based on empirical data and theory [1]. The region is limited, calculating accuracy is low and the design is not comprehensive. Compared with traditional computing method, air-gap field and eddy current distribution of mechanism can be described more comprehensively and more accurately by using finite element method. Therefore, this paper studies the field of magnetic transmission mechanism of downhole turbine generator by using ANSYS software.

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2. MAGNETIC TRANSMISSION MECHANISM AND ITS FINITE ELEMENT MODEL

2.1. Magnetic Transmission Mechanism

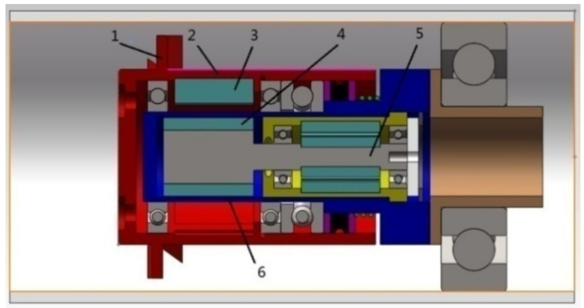
The structure of new designed turbine generator is shown in Fig. (**1**) [2]. Its principle is that the mud rotates turbine, magnetic drive shell 2 and rotates the permanent magnet 3 which are integrated with the turbine. The distance sleeve 6 is installed between the outer magnetic rotor 3 and inner magnetic rotor 4, so that inner magnetic rotor 4 follows with outer magnetic rotor 3 rotating, synchronously. The generator rotating shaft 5 which is connected with inner magnetic rotor 4 rotates as well, and the power is generated [2].

2.2. 2D Finite Element Models for Calculating Magnetic Field

In order to reduce the calculation, magnetic transmission mechanism of turbine generator model is simplified by using 2D finite element model. The model remains in the XY plane of global coordinate system, the magnetic flux density is only calculated in this plane. In order to analyze more conveniently certain assumptions are made:

(1) Model is considered having indefinite length, ignoring the edge effect;

(2) Outside and inner yoke on magnetic rotor are magnetized, there is no magnetic saturation in yoke;



1-turbine; 2-shell; 3-outside magnetic rotor; 4- inner magnetic rotor; 5- generator rotating shaft; 6-distance sleeve

Fig. (1). The structure of turbine generator.

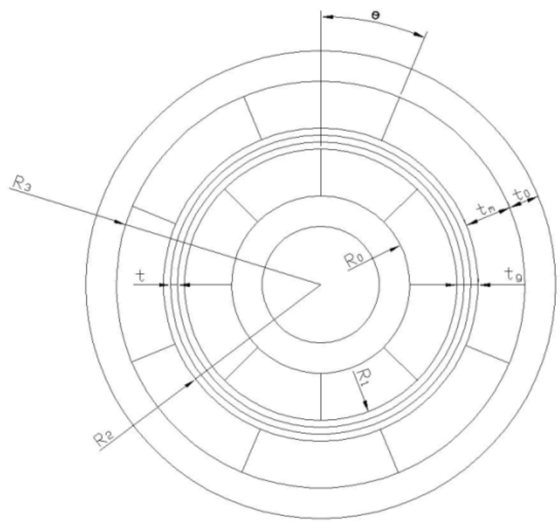


Fig. (2). Magnetic transmission mechanism of 2D structure.

(3) On the cross section, the geometric and physical factors of magnetic rotor are changed periodically.

The calculation of finite element analysis of the magnetic field is based on the magnetic vector Z component [3]. Two equations of magnetic-field component in Maxwell's equations are:

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla\times\mathbf{B} = \varepsilon_0\mu_0\frac{\partial \mathbf{E}}{\partial t} + \mu_0\mathbf{j_0}$$

In formula, ∇ is a divergence operator; $\nabla\times$ is rotation operator; B is magnetic flux density vector; E is electric intensity vector; j_0 is total current density; ε_0 is permittivity; μ_0 is permeability.

Magnetic vector potential A is introduced in model, its rotation is magnetic flux density B, [6] that is

$$B = \nabla\times A$$

Maxwell's equations can be simplified as follows:

$$\nabla\times\nabla\times A = \varepsilon_0\mu_0\frac{\partial E}{\partial t} + \mu_0 j_0$$

The type can be simplified if the chosen A can meet $\nabla \cdot A = 0$

$$-\nabla^2 A = \varepsilon_0\mu_0\frac{\partial E}{\partial t} + \mu_0 j_0$$

In the static magnetic field, $\frac{\partial E}{\partial t} = 0$, so it can be simplified to solve Poisson equation

$$\nabla^2 A + \mu_0 j_0 = 0$$

In 2D plane, component of B is only considered in XY plane, so magnetic vector is just Z. Thus the equation can be simplified as follows:

$$\nabla^2 A_z + \mu_0 j_{0_z} = 0$$

The constitutive relation with electric field should be considered if conductor involves speed effect [4, 5].

$$j = \sigma[E + v\times B]$$

In formula, σ is conductivity of conductor; v is velocity vector of conductor.

2.3. Establishing 2D Finite Element Model

2.3.1. Preprocessor [7-12]

(1) Solid modeling. Fig. (**2**) is magnetic transmission mechanism of 2D structure. Model parameters are shown

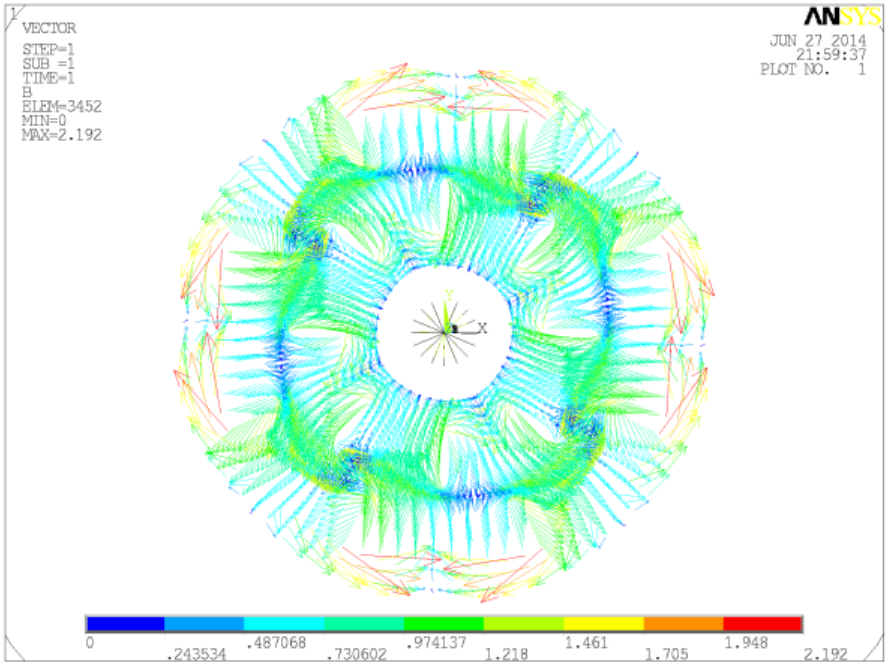


Fig. (3). Distribution of magnetic flux density.

in **chart 1**. The material between inner and outer is air, yoke, magnets, air, distance sleeve, air, magnets, yoke, air, and the structure of magnets is 8 poles.

Chart 1. Model parameter

Symbol	Name
R_0(mm)	Inner diameter of inner magnet
R_1(mm)	Outer diameter of inner magnet
R_2(mm)	Inner diameter of outer magnet
R_3(mm)	Outer diameter of outer magnet
θ(°)	Corner
t_g(mm)	Air gap
t_0(mm)	Thickness of yoke
t_m(mm)	Thickness of magnetic sheet
m	Number of magnetic poles
t(mm)	Thickness of distance sleeve

(2) Element type is PLANE53. This paper used nodal method to analyze static magnetic field and eddy current in distance sleeve, so PLANE53 is chosen. In practice, inner and outer magnetic rotor rotates synchronously, distance sleeve is stationary. While in finite element analysis, rotated magnetic field converts static field, inner and outer magnets are stationary, specific speed effect is applied on distance sleeve, that is distance sleeve rotates, its speed is the rotational speed of the magnets.

(3) Material property. The property of air, yoke, magnets and distance sleeve are defined respectively. Magnets is samarium cobalt, its permeability is 1.05, the coercivity is 750000A/m; yoke is silicon steel, its relative permeability is 700; distance sleeve is chrome nickel, its relative permeability is 3, electrical resistivity is 7.194e-7Ω·m.

(4) Meshing. Quadrilateral is chosen for meshing. In order to improve the accuracy, the whole air gap is meshed finer because of the torque between the inner and outer magnets are determined by the air gap magnetic field.

(5) Magnets magnetized in radial direction are defined by using local coordinate system.

2.3.2. Solution

(1) Setting the boundary conditions. Imposing parallel flux on the boundary between inner and outer, that is each nodes on the boundary A_z is 0; defining the component and applying a force on it.

(2) Selecting everything and then solving the static field.

2.3.3. General Post-Processing

The distribution of magnetic flux density is shown in Fig. (**3**), the circular-distributed curve of magnetic flux density B in the outer diameter of inner magnet is shown in Fig. (**4**). Red and yellow lines in Fig. (**3**) indicate that the field density is strong, the maximum is 2.192T. In Fig. (**4**), the field density in the outer diameter of inner magnets is distributed regularly in circumference, the maximum is 1.276T.

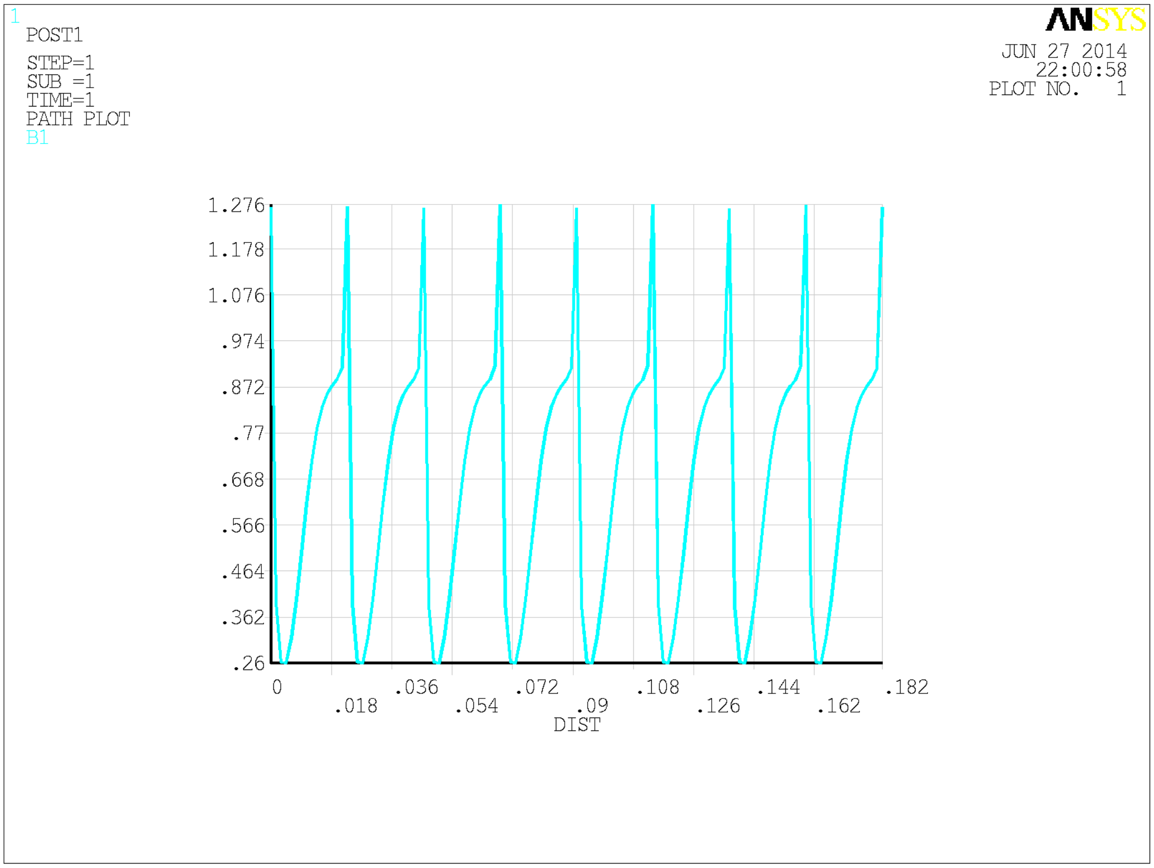


Fig. (4). The field density in the outer diameter of inner magnet.

3. ANALYSIS OF THE FINITE ELEMENT RESULT

The effects of thickness of permanent magnets, thickness of distance sleeve, the average radius of working field, air gaps and rotating speed on torque were quantitatively analyzed by using 2D magnetic transmission mechanism model which is established in ANSYS [13, 14].

3.1. The Effect of Thickness of Magnet Poles on Torque

Magnets provide magnetic potential in magnetic circuit, the larger the air magnetic density, the larger the torque in magnetic circuit [1]. Guaranteeing the yoke unsaturation, the following variable parameters are applied, t_g=4.5mm, t=1.5mm, θ=22, m=8, t_0=6.5m, rotating speed is n=1200r/min. Then changing the thickness of magnetic poles, t_m is valued 6mm, 7mm, 8mm, 9mm, and 10mm. Because the distance sleeve is located in the periodic variation magnetic field, while it is cutting the magnetic flux, eddy current is generated.

Eddy current distribution is shown in Fig. (**5**). The relationship between thickness of magnetic pole and torque is shown in Fig. (**6**). The relationship between thickness of magnetic poles and maximum eddy current in distance sleeve is shown in Fig. (**7**).

From Fig. (**6**), it can be concluded that magnetic torque is increasing with the increase of thickness of the poles. However, from Fig. (**7**), it can be seen that with the increase of thickness, the eddy current in the distance sleeve is also increasing, so a lot of increased magnetic potential caused by increasing thickness is consumed in the distance sleeve, and the effective contribution to the magnetic circuit is reduced. Therefore, in order to improve the utilization rate and reduce the cost, the thickness of magnets cannot be increased endlessly to get the larger torque during the design.

3.2. The Effect of Thickness of Distance Sleeve on Torque

In theory, by reducing the thickness of the sleeve, eddy current will be smaller, and the torque will be larger. The following variable parameters are applied when the effect of thickness of distance sleeve on torque is studied, t=1.5mm, θ=22É , m=8, t_0=6.5mm, average radius $R_c=\frac{1}{2}(R_1+R_2)$ =31.25mm , rotating speed n=1200r/min . Then changing the thickness of distance sleeve, t is valued 0.5mm, 1mm, 1.5mm, 2mm, and 2.5mm. The relationship between the thickness of distance sleeve and torque is shown in Fig. (**8**). The relationship between the thickness of distance sleeve and maximum eddy current in distance sleeve is shown in Fig. (**9**).

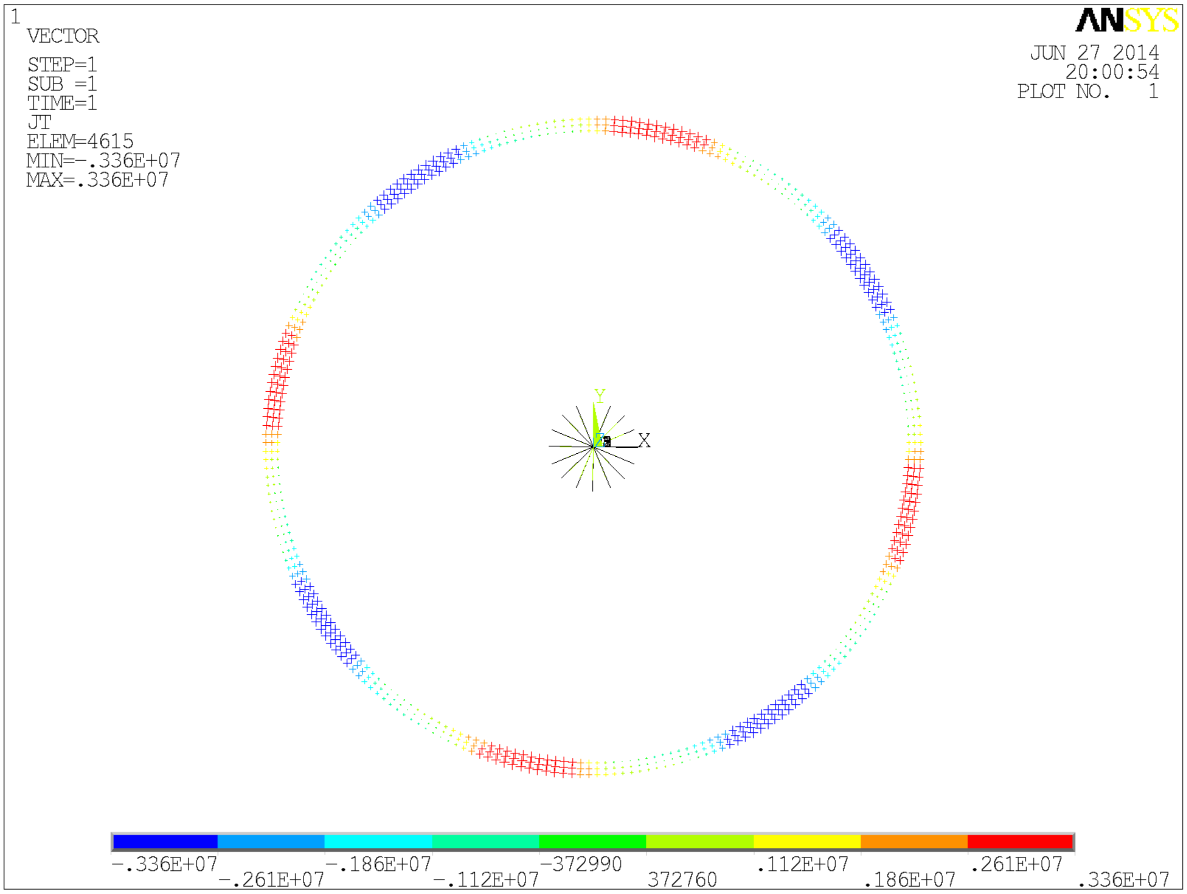


Fig. (5). Distribution of eddy current density in distance sleeve when t_m=6mm.

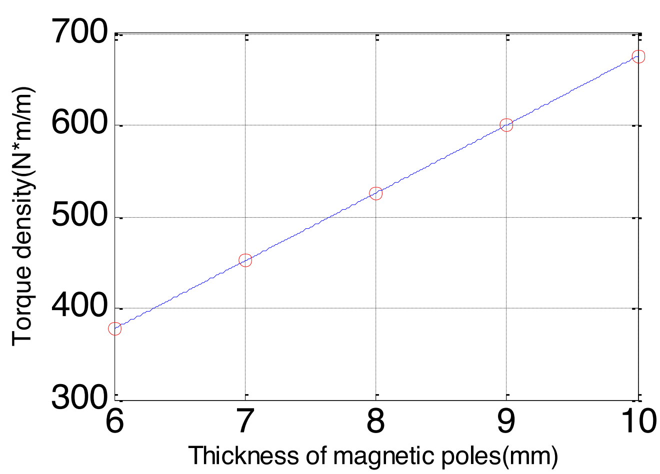


Fig. (6). Relationship between thicknesses of magnetic poles and torque density.

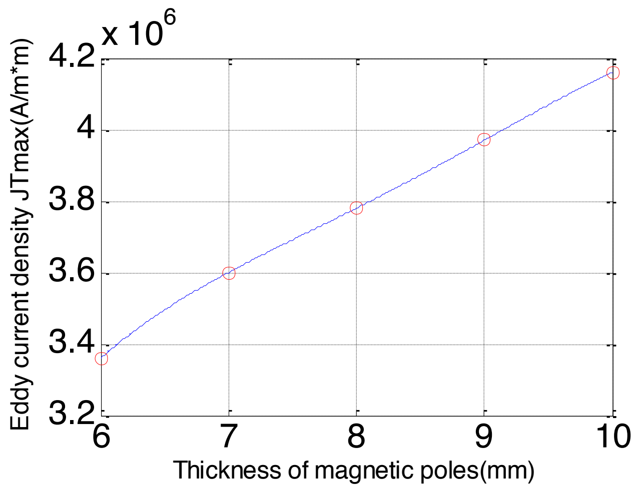


Fig. (7). Relationship between thickness of magnetic poles and eddy current density in distance sleeve.

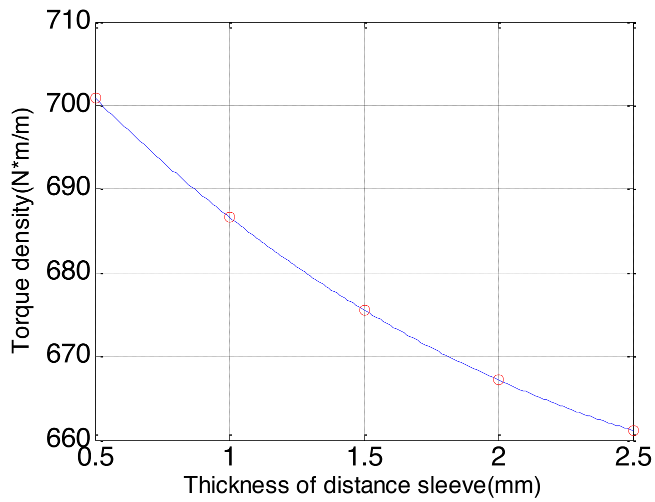


Fig. (8). The relationship between the thickness of distance sleeve and torque density.

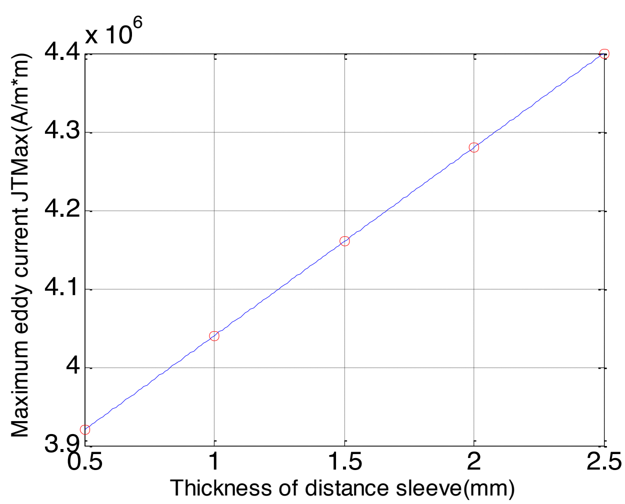


Fig. (9). The relationship between the thicknesses of distance sleeve and maximum eddy current.

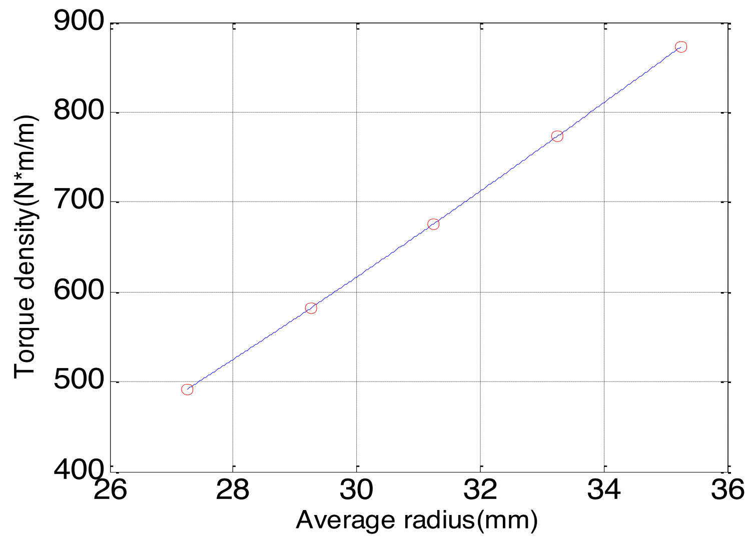


Fig. (10). The relationship between R_c and torque.

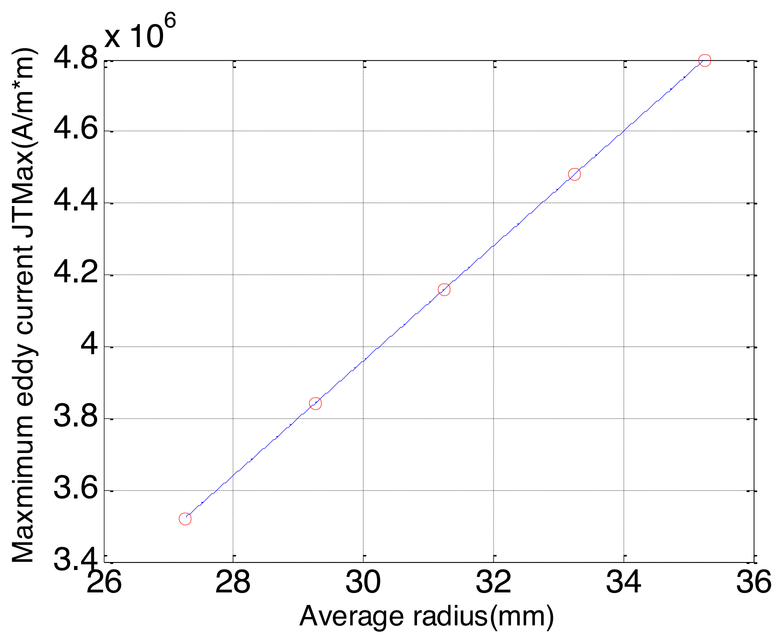


Fig. (11). The relationship between eddy current and radius.

From Fig. (**8**), it can be concluded that the torque is smaller with the increase of thickness of distance sleeve. Due to the increased thickness, the total air gap is enlarged. The magnetic flux density that is reduced by the air gap must be remedied. In addition, it can be seen in Fig. (**9**) that eddy current is larger because of increased thickness of distance sleeve, and the consumption of magnetic potential is increased. As mentioned earlier, the torque can be enhanced by reducing the thickness of distance sleeve, while practically, the distance sleeve must meet the requirements of downhole pressure. Thus on the premise of meeting the requirements, the thickness of distance sleeve should be as thin as possible.

3.3. The Effect of Magnetic Action Average Radius on Torque

The following variable parameters are applied when the effect of average radius of working field on torque is studied, with t_g=4.5mm, t=1.5mm, θ=22°, m=8, t_0=6.5mm, t_m=10mm, rotating speed n=1200r/min. Changing the average radius of working field, $R_c=\frac{1}{2}(R_1+R_2)$, R_c is valued 27.25mm, 29.25mm, 31.25mm, 33.25mm, and 35.25mm. The relationship between R_c and torque is shown in Fig. (**10**). Eddy current in distance sleeve is different with different radiuses, and the relationship between them is shown in Fig. (**11**).

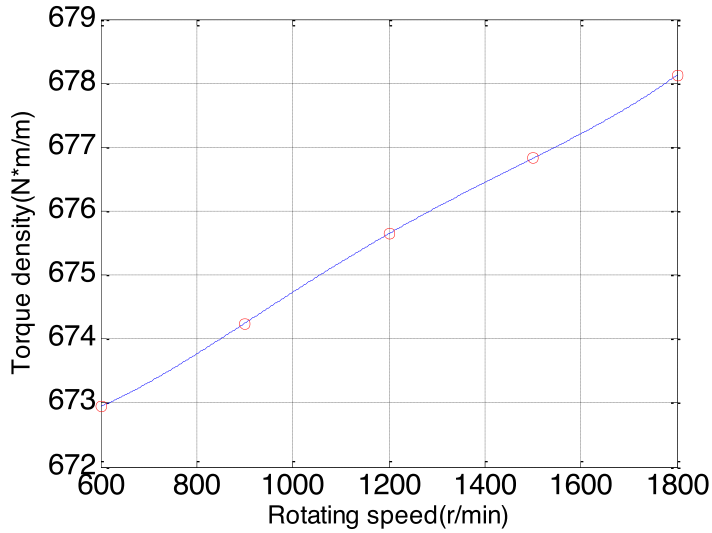


Fig. (12). The relationship between rotating speed and torque.

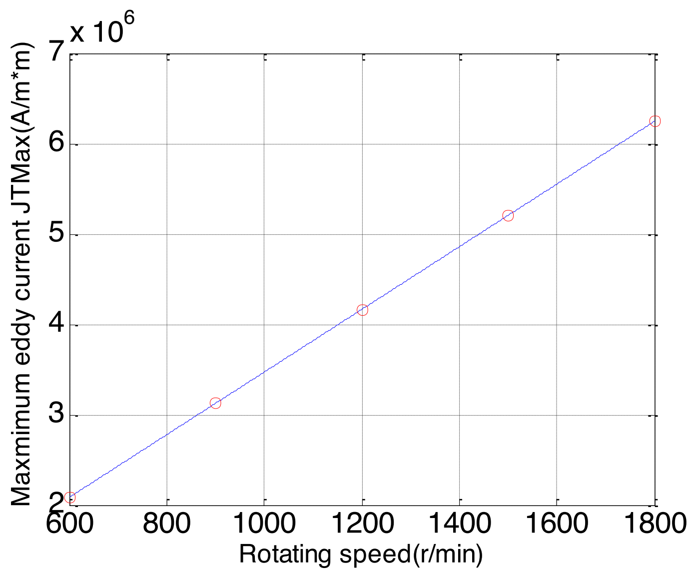


Fig. (13). The relationship between rotating speed and eddy current.

From Fig. (**10**), it is concluded that torque density increases with increased radius [15]. However, eddy current is larger with increased torque from Fig. (**11**). The limitation of structure, eddy current and other factors must be considered when magnetic transmission mechanism is designed, and the average radius should not be too large.

3.4. The Effect of Rotating Speed on Magnetic Torque

The following variable parameters are applied when the rotating speed is studied, t_g=4.5mm, t=1.5mm, θ=22°, m=8, t_0=6.5mm, t_m=10mm, $R_c=\frac{1}{2}(R_1+R_2)$ =31.25mm. Changing the rotational speed, it is valued 600r/min, 900 r/min, 1200 r/min, 1500 r/min, and 1800 r/min. The relationship between rotating speed and torque is shown in Fig. (**12**). The relationship between rotating speed and eddy current in distance sleeve is shown in Fig. (**13**).

From Fig. (**12**), it is concluded that the torque density is enhanced with the increased rotation speed. But in figure 13, it is seen that eddy current is rising sharply with the increased rotation speed. Magnetic torque can be enhanced appropriately when the rotating speed is designed, but if the speed is too high, the magnetic eddy current will be obvious, which will impact the distance sleeve and normal operation. If the eddy current is rising sharply, and the temperature of the distance sleeve reaches a certain degree, then the magnets will demagnetize and then magnetic

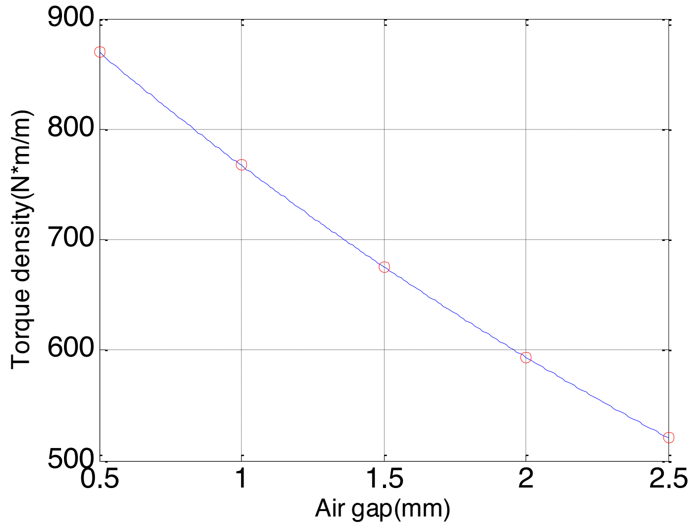


Fig. (14). The relationship between unilateral air gap and torque.

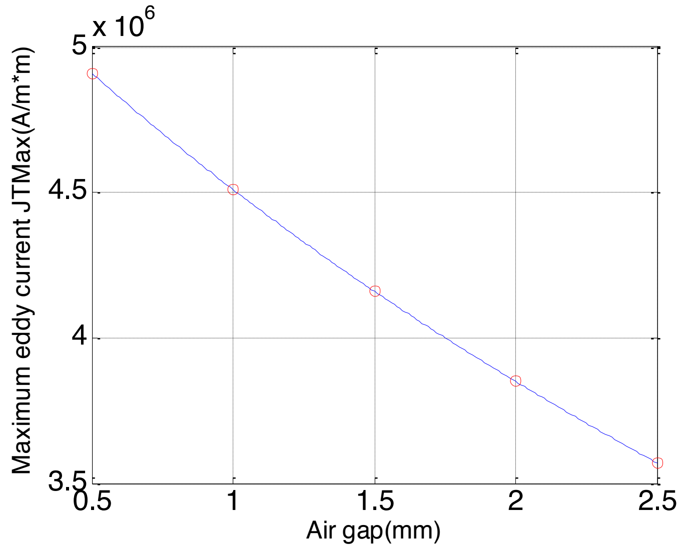


Fig. (15). The relationship between eddy current and unilateral air gap.

action will fade away. The magnetic transmission will be a failure.

3.5. The Effect of Air Gap on Magnetic Torque

The following variable parameters are applied to study the effect of the air gap on magnetic torque. t=1.5mm, θ=22É, m=8, t_0 =6.5mm, t_m =10mm, $R_c=\frac{1}{2}(R_1+R_2)$ =31.25mm, rotating speed is n=1200r/min. Changing the thickness of unilateral air gap, it is valued 0.5mm, 1mm, 1.5mm, 2mm, and 2.5mm, so the total air gap is 2.5mm, 3.5mm, 4.5mm, 5.5mm, and 6.5mm. The relationship between unilateral air gap and torque is shown in Fig. (**14**). The relationship between eddy current and unilateral air gap is shown in Fig. (**15**).

From Figs. (**11** and **15**), it can be concluded that the torque density and eddy current in distance sleeve is dropping sharply along with increased thickness of air gap. Reduction of magnetic potential in the air gap is increasing because of increased thickness of air gap, which leads to decrease of torque and eddy current. In order to make full use of the valuable magnetic material, the air gap should be reduced. But if the gap is too thin, eddy current will be obvious, and the normal operation will be influenced. Other factors that might also have an influence are: misalignment during assembling, vibration between inner and outer rotors and so on, which will require high quality mechanical processing and assembly. From the above it can be deduced that the air gap should be determined after comprehensive consideration.

CONCLUSION

This paper focused on the magnetic transmission mechanism of a turbine generator and calculated the magnetic field by using finite element simulation. Based on the principle of magnetism, torque and eddy current of distance sleeve were calculated by using ANSYS software, the following conclusions were obtained:

(1) Compared with traditional calculation method, on the premise of ignoring edge effect and no magnetic saturation in yoke, mechanism is simplified to 2D model and is analyzed by using ANSYS software and equivalent static magnetic method. The air magnetic field and eddy current can be described comprehensively which has a certain practical value.

(2) In 2D model, torque and eddy current will be changed with the changing structural parameters. The basic rule is: torque and eddy current density will be enlarged with the increase of the thickness of magnets, increase of average radius, and increase of rotating speed. Torque will be enlarged while eddy current will be reduced with the increasing thickness of distance sleeve. Torque and eddy current will be both reduced with the increasing working air gap. Therefore, the influence of eddy current in distance sleeve should be considered when designing the transmission mechanism to avoid reducing large torque. The size of magnetic transmission mechanism should be optimized for the design goal of large torque and low eddy current, avoiding overheating, and making sure that the generator can work normally.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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