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Analysis Research for PMC System Considering Conductor Disk

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Abstract. It is essential to optimize the conductor surface vortex path because the efficiency of Permanent magnet governor depends on the excitation level of the induced current. In order to further improve efficiency, this article focuses on a permanent magnet governor with slotted conductor disk. The 2D and 3D dynamic simulation model are established and the characteristics of slotted and plain structure are analyzed. The results are shown that the vortex path of the permanent magnet governor with slotted structure is optimized, the magnetic flux leakage is reduced, and the thermal capacity is higher. The transmission torque mathematical model with temperature parameters is established considering the transmission torque. The transmission torque is affected by conductivity changing with the conductor disk heating. The effects of temperature changing and relative speed on torque transmission are analyzed. Finally, the torque characteristics of slotted and plain structure were compared by the experimental test under different conditions. It is proved that the slotted structure can improve the transmission efficiency and reduce the vortex field impact due to the temperature of conductor disk rising. And it is verified that the mathematical model is valid.

Keywords: adjustable permanent magnetic coupler, slotted conductor, finite element, stray current, moving eddy current field

1 Introduction

The adjustable permanent magnetic coupler has been the hot topic in the researches conducted by domestic and foreign scholars since 1999. [1] Currently it has been applied to industries such as pumps and blowers. [2] In comparison with frequency convertors with efficiency at 95%, its efficiency is a little bit lower (93%) but it has remarkable advantages: it uses purely mechanical non-contact type of structure to effectively remove power harmonic pollution, electromagnetic interference, avoid transmission between motor and load through vibration and truly realize green and energy conservation. In order to further improve the efficiency of the adjustable permanent magnetic coupler, it is necessary to deal with the stray current on conductor disc and optimize eddy current path. The above-mentioned currents form eddy current consumption through the heat produced on the conductor disc and the

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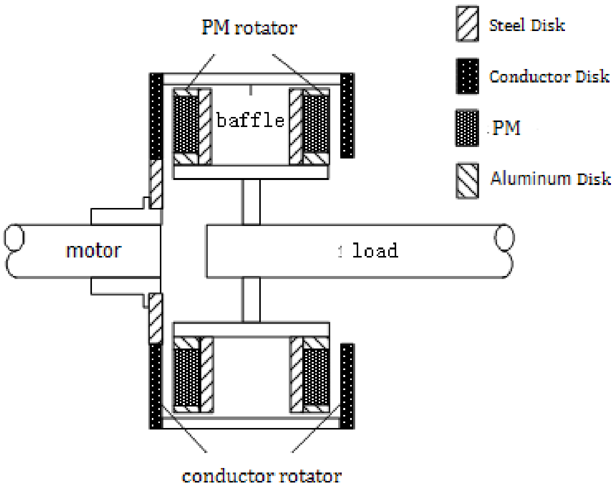
generated heat not only wastes energy but also disturbs the magnetic performance of permanent magnet and reduces the system's ability in torque transmission.

In recent years, scholars have conducted researches on permanent magnet transmission with certain achievements. In Document [3], it conducts analysis and comparison of magnetic circuit arrangement in plain structure and it points out to select relevant parameters to effectively control the amount of eddy current loss. In Document [4], it sets up the 3D finite element model of eddy current field for plain structure, calculates electromagnetic field distribution and summarizes the principle of selecting major parameters. The above-mentioned researches focus on optimizing parameters to improve transmission performance through analyzing model and simulation result without structural improvement based on practice. Secondly, both analysis model and simulation model are simplified with consideration of only the influence on transmission performance by major parameters and it fails to consider the influence brought by factors such as temperature, vibration and mal-alignment, etc.

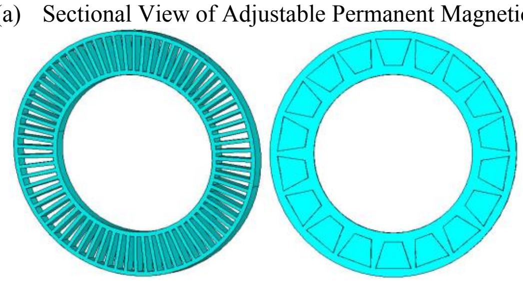
In this paper, it puts forward a new type of conductor disc design method. In this design, ladder-shaped slot exists in conductor disc for the convenience of promoting the flowing of eddy current along the appropriate path, optimize eddy current path and avoid the production of stray current. Besides, it also helps improve the adjustable permanent magnetic coupler improve its radiation ability and reduce the influence on performance brought by temperature. In this study, firstly, it is necessary to use ANSYS Finite Element Analysis Software to set up the 2D dynamic simulation model for adjustable permanent magnetic coupler with plain/slotted structure. It will conduct the simulation results of the magnetic field distribution in these two structures to verify the high efficiency of slotted structure. Secondly, it is necessary to set up mathematical model and 3D simulation model for the slotted structure to analyze distribution principle of 3D moving eddy current field, magnetic field and thermal energy and exhibit the optimized result of eddy current path. Finally, it will use the experiment to verify the effectiveness of improving torque transmission in slotted structure and the precision of the calculation method.

2 Working Principle and Mechanical Design

The structure of adjustable permanent magnetic coupler with slotted structure is as illustrated in Diagram 1 (a) and it is mainly divided into two parts: the first part is the conductor disc connected with motor; the second part is the permanent magnetic disc connected with the load terminal. Use copper disc as the conductor disc. Permanent disc is composed of aluminum disc, steel disc and NdFeB permanent Magnet and there is air gap between it and the doctor disc. When motor is rotating, conductor disc will cut magnetic curves to form eddy current circuit in the surface so as to generate conduction magnetic field. It is necessary to the mutual functions of magnetic fields to enable the permanent magnetic rotator keep rotating with load and conductor disc in the same direction. Load end is connected with air gap adjustment device. Besides, adjust two permanent rotators to conduct anti-clockwise action so as to change the gap between airs and to keep output rotating speed under control.



(a) Sectional View of Adjustable Permanent Magnetic Coupler



(b) Slotted Conductor Disc and Permanent Magnetic Disc

Fig.1 Structure diagram of adjustable permanent magnetic coupler

In order to optimize vortex circulation path, it opens 72 ladder-shaped slots on the conductor disc as illustrated in Fig 1 (b). In the Fig, the ladder-shaped slot dimension is as follows: upper edge – 8mm; lower edge – 4mm; height – 40mm; thickness – 10mm. In order to cooperate with the vortex circuit on copper disc, the permanent magnet uses ladder-shaped magnet with N and S poles alternatively arrayed on the steel backing disc. In Fig 1 (b), the dimension of the ladder-shaped magnet is as follows: upper edge – 40mm; lower edge – 20mm; height – 30mm; thickness – 20mm. select the same surface, use ANSYS finite element analysis software to establish 2D dynamic simulation model for adjustable permanent magnetic coupler with slotted structure and conduct analysis of amount of the relevant electromagnetic field. Simulation parameters are as follows: steel disc length – 80.28mm; thickness – 10mm; copper disc length -- 80.28mm; thickness – 10mm; air gap – 3mm; motor output rotation speed -- 1455r/min. F

3 Analytical Model of Transmission Torque in Slotted Structure

In the process of calculating T – magnetic transmission torque, in the angle of calculus, we can treat the copper disc as the combination of infinite copper stripes with multiple lengths (r2-r1) sharing the same center of circle in tight arrangement. When the adjustable permanent magnetic coupler is working, the existence of slip makes the relative angular speed of copper disc at ωn and the intensification of magnetic induction vertically going through the copper disc is at B. Eddy current is induced on copper disc. Relative to permanent magnetic plate rotation, copper is equal to cutting numerous magnetic forces of lines conducted by loaded conduction lines to produce magnetic transmission torque on the copper disc as illustrated in Fig 3:

In which, dl is copper disc's radial infinitesimal element; dθ is the copper disc's circumferential infinitesimal element; ε is motional electromotive force on copper disc;Based on Document, we can see that effective value Ie of eddy current on copper disc is:

$$I_e = \frac{\sigma B v}{2} \tag{1}$$

In which, ν is the relative linear speed of copper disc and permanent magnetic plate with ν=ωnl and unit at m/s. ωn is the relative angular speed of copper disc and permanent magnetic plate. σ is conductivity. Eddy current di within dθ curve on copper disc is:

$$di = \frac{I_e}{2\pi} d\theta \tag{2}$$

In which, dθ is the copper disc's circumferential infinitesimal element with unit at rad; Based on Ampere's law, we can obtain Ampere's force dF and magnetic transmission torque dT at length of dl on the copper disc is:

$$dF = Bdidl \tag{3}$$

$$dT = ldF \tag{4}$$

In which, dl is copper disc's radial infinitesimal element with unit at m; l is radial torque of the infinitesimal element with unit at m; introduce formula (2), (3) and (4) in it and we can obtain:

$$dT = \frac{BI_e}{2\pi} ld\theta dl \tag{5}$$

Based on integration of (5), we can obtain magnetic transmission torque Tat:

$$T = \int_{r_1}^{r_2} \int_0^{2\pi} \frac{BI_e}{2\pi} ld\theta dl \tag{6}$$

Introduce (1) to (6) and simplify it to obtain:

$$T = \frac{\sigma B^2 \omega_n \left(r_2^3 - r_1^3 \right)}{6} \tag{7}$$

The eddy current produced on the copper disc radiates heat to lower conductivity σ of copper disc. When temperature change is large, the calculation of transmission torque needs to consider the influence brought by changes of temperature on σ. The formula for σ with the change of temperature is as follows:

$$\sigma = \frac{1}{\rho_0 (1 + \alpha t)} \tag{8}$$

In which, ρ_0 is resistivity at zero degree with value at 1.678×10-8 and α is temperature coefficient with value at 0.004; t is centigrade temperature. Introduce formula (8) to (7) and we can obtain transmission torque in different temperatures as follows:

$$T = \frac{B^2 \omega_n \left(r_2^3 - r_1^3 \right)}{6 \rho_0 (1 + \alpha t)} \tag{9}$$

4 Slotted Structure's Finite Element and Characteristic Analysis

4.1 Modeling

Magnetic field generated by eddy current changes with the time [7-9] and it belongs to time-varying field. In low frequency, effect of displacement current is omitted and we can obtain basic equation as follows:

$$\begin{cases} \nabla \times \boldsymbol{H} = \boldsymbol{J} \\ \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial \boldsymbol{t}} \\ \nabla \cdot \boldsymbol{B} = 0 \end{cases} \tag{10}$$

In the formula: H — magnetic field intensity, A/m; J— conduction current density, A/m2； B— magnetic flux density, T.

Additional constituent equation:

$$\begin{cases} \boldsymbol{J} = \sigma \boldsymbol{E} \\ \boldsymbol{B} = \mu \boldsymbol{H} \end{cases} \tag{11}$$

In the formula, σ—conductivity; E—electric field strength, V/m; μ—magnetic permeability. Flux density B can be displayed by magnetic vector potential A and the expression is as follows:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{12}$$

There is no source current input in the adjustable permanent magnetic coupler, there is no source current density in overall domain and there is only vertex density on surface of copper ring. Vortex density expression is as follows:

Adopt A, Φ-A Method [10-11] to establish the mathematical model of vortex field and in overall domain, it is divided into vortex area V1, permanent magnet area V2 and air area V3. The control equation in each area is as follows:

$$\begin{aligned} &\text{V1:}\ \nabla \times \left(\frac{1}{\mu} \nabla \times \boldsymbol{A} \right) + \sigma \nabla \phi - \sigma \left[\boldsymbol{V} \times \left(\nabla \times \boldsymbol{A} \right) \right] = 0 \\ &\text{V2:}\ \nabla \times \frac{1}{\mu} \left(\nabla \times \boldsymbol{A} - \boldsymbol{B}_r \right) = 0 \\ &\text{V3:}\ \nabla \times \frac{1}{\mu} \left(\nabla \times \boldsymbol{A} \right) = 0 \end{aligned} \tag{13}$$

In the formula: Br—residual flux density of permanent magnet; based on the above-mentioned control equation group, we can see that the moving speed of conduct V is a constant and there is no derivative t related to time. Impose flux on the peripheral boundary of overall domain the parallel boundary condition and use magnetic vector potential A and scalar potential Φ to find the flux density B, current density J and other amount of magnetic field in the area.

In this paper, it uses ANSYS software to conduct 3D dynamic finite element modeling for adjustable permanent magnetic coupler with slotted structure and it analyzes the relevant magnetic field amount. The permanent magnet selects NdFeB with specification of N38H, copper disc uses brass with model number at H62 and steel disc uses No.45 steel. As to structure dimension, in addition to using 2D simulation parameters, the other relevant parameters are as follows: copper disc internal radius – 90mm, external radium 140 mm; steel disc internal radius – 90mm, external radium 140 mm; amount of permanent magnet – 18; number of ladder-shaped slots – 72; motor output rotation speed -- 1455r/min.

5 Conclusion

1) Based on the static magnetic field analysis of the adjustable permanent magnetic coupler in slotted structure, we understand that magnetic flux density is elevated in

magnetic circuit and the magnetic leakage in the magnetic circuit descends. It establishes the 3D moving eddy current field to conduct dynamic analysis and we know that eddy current mainly flows along the radial direction and the its path is optimized to avoid the production of stray current;

2) Eddy current heat elevates the resistivity of the conductor disc, which leads to the re-distribution of eddy current field and reduce the transmission efficiency. In this paper, based on the experiment, it proves that the conductor disc with slotted structure is beneficial for heat radiation and it reduces the influence on eddy current field caused by elevation of resistivity of conductor disc due to eddy current heat;

3) The experiment proves that as to the two structures, under the condition of same air gap, same relative rotation speed and same axial offset, the slotted structure can elevate transmission torque; it also proves that the transmission torque in slotted structure is related to the number of ladder-shaped slots and only when the number of ladder-shaped slots is above 60, the efficiency of the slotted structure can obviously elevate the efficiency in comparison with plain structure.

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