Modulated Magnetic Gear Dynamic Improvement of Damper Winding

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Abstract: With the development of the power era, the position of electric drive in the field of transmission is becoming more and more important. However, from the perspective of economy and other aspects, it is not realistic to realize direct electric drive, so gear plays an important role in this development. Traditional mechanical gears have problems in many aspects and cannot meet the needs of development. Modulated gear is a non-contact magnetic transmission device that can solve the problem of traditional mechanical gears. However, when the start-up and load and speed changes, modulated gears will experience transient oscillations. In order to solve this problem, this paper proposes a dynamic improvement study of modulated magnetic gears with damper winding. Studies have shown that the addition of the damper winding can effectively reduce the time required for the magnetic gear to reach the steady state and the amplitude of the oscillation attenuation, so that the dynamic performance of the entire system can be improved.

1. Introduction

In the transmission system, the mechanical gear is usually directly transferred by the meshing of the teeth between the input and the output to achieve torque transmission and speed change. In many modern industrial applications, the gearbox and the transmission are used between the prime mover and the actuator to match the speed and transmit torque, and occupy a very important position in today's mechanical applications. Therefore, traditional mechanical gears are rapidly developing in the direction of "high precision, high speed, high transmission efficiency and high tooth surface hardness" [1, 2]. With the development of the national economy and the continuous improvement of the level of the department level, although the technological level of the mechanical gear has been gradually improved, the problems of vibration, noise and mechanical loss, periodic lubrication brought about by the operation have not been fundamentally solved.

Compared with the traditional mechanical gear, the input and output of the modulated magnetic gear are non-contact and have the characteristics of overload protection. These characteristics of the magnetic gear make it a special advantage in the practical application of torque and speed transmission. Nowadays, there are many types of magnetic transmission, such as magnetic gears and magnetic couplings [3]. These magnetic transmissions can realize the mechanical connection between the prime mover and the working machine. Relying on magnetic lines to achieve synchronous movement between the prime mover and the working machine. As the magnetic permeability of permanent magnet materials continues to increase, the ability of magnetic gears to transmit torque is also increasing. Therefore, in some practical applications of torque and speed transmission, the use of magnetic gears instead of the traditional mechanical gearbox and transmission, combined with the motor drive, can solve many unfavorable problems caused by mechanical gears such as noise, wear and vibration. However, the non-rigid magnetic coupling between the two rotors of the magnetic gear results in transient oscillations at start-up and changes in load and speed.

The generator damper winding is mainly to prevent the generator from impacting the generator

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winding when the load suddenly changes. When the load changes, the voltage and current in the winding will form a oscillating process. The damper strip is to increase the resistance to the oscillating process, forming a damping oscillating motion, thereby forming a certain buffering effect. The damper winding is the key structural component that affects the stable operation of the generator motor. It is of great theoretical significance and practical value to study the electromagnetic force under the power generation condition of the abnormal operating state. When the main rotor is shaped, the damper winding performance of the rotor is the most important factor affecting the super-transient reactance [4]. Liu Wei studied the electromagnetic force of the damper winding of the generator motor under abnormal operation [5]. In his research, he took the generator motor as the research object and revealed the variation law of electromagnetic force under abnormal operating conditions.

At present, a large number of researches on magnetic gears are mainly aimed at their static and steady-state performance, and there are few research methods on the dynamic performance of magnetic gears. In this paper, combined with the working characteristics of the low torsional stiffness of the magnetic gear and the working principle of the damper winding in the permanent magnet synchronous motor, we propose a modulated magnetic gear model with a damper winding added to the high speed rotor side. And we have optimized the design, dynamic performance analysis and so on.

2. Methods

2.1 Modulation type magnetic gear structure design

The structure of the modulated magnetic gear mainly includes an inner rotor composed of an inner yoke iron, an outer rotor composed of an outer yoke iron, an inner and outer rotor permanent magnet, an inner and outer rotor air gap, and a magnetic modulating ring composed of a magnetic conductive material and a non-magnetic conductive material. In order to improve the stability of the system, reduce the magnetic flux leakage between adjacent magnetic poles and improve the transmission efficiency, the magnetic gear inner rotor proposed in this paper adopts a salient pole rotor structure similar to synchronous motor. This structure introduces a damper winding on its high-speed rotor side, so that when the magnetic gear is activated and subjected to sudden transient disturbance, an induced current is generated in the damper winding, thereby generating damping torque to suppress oscillation of the system.

2.2 Modulation magnetic gear analysis principle

When the inner rotor having p poles rotates at the rotational speed Ω_r, a spatially distributed magnetic field is formed in the rotor air gap. The magnetic field produces a radial and tangential component of the magnetic induction at a radius r and an angle θ. Recorded as $B_r(r,\theta)$, $B_\theta(r,\theta)$. The magnetic induction intensity of the air gap magnetic field can be expressed by the equations (1), (2) when the magnetic field modulation is performed without the magnetic flux ring.

$$B_r(r,\theta)=\sum_{m=1,3,5\ldots}^{\infty} b_{rm}(r)\cos\left(mp(\theta-\Omega_r t)+mp\theta_0\right) \tag{1}$$

$$B_\theta(r,\theta)=\sum_{m=1,3,5\ldots}^{\infty} b_{\theta m}(r)\sin\left(mp(\theta-\Omega_r t)+mp\theta_0\right) \tag{2}$$

The number of the magnetic flux ring is recorded as n_s, and the rotational speed of the magnetic ring is recorded as Ω_s. When the magnetic flux ring participates in the magnetic field modulation, the ratio of the magnetic permeability of the magnetic flux ring in the air gap to the air gap permeability of the permanent magnet alone is called the modulation function λ:

$$\lambda=\lambda_0+\sum_{j=1,3,5\ldots}^{\infty}\lambda_j\cos\left(jn_s(\theta-\Omega_s t)\right) \tag{3}$$

Where λ_0 is the constant component coefficient of the modulation function and λ_j is the Fourier decomposition coefficient.

The harmonics generated by the magnetic field generated by the inner rotor permanent magnet after the modulation of the magnetic flux ring are:

$$p_{m,k} = |mp + kn_s|; \quad m = 1,3,5,\cdots\infty; k = 0,\pm1,\pm2,\cdots\infty \tag{4}$$

The rotational speed of the magnetic field space harmonics is:

$$\Omega_{m,k} = \frac{mp}{mp + kn_s}\Omega_r + \frac{kn_s}{mp + kn_s}\Omega_s \tag{5}$$

When $k = 0$, $\Omega_{m,k} = \Omega_r$ is satisfied. That is, the inner rotor speed is equal to the rotational speed of the magnetic field space harmonics. At this time, the magnetic flux ring does not function, similar to $\Omega_s = 0$, only the basic harmonic magnetic field exists, and the shifting motion of the magnetic gear cannot be realized.

When $k \neq 0$, the rotational speed of the modulated harmonic magnetic field is no longer equal to the inner rotor rotational speed. This is because the spatial harmonic magnetic field generated by the inner rotor permanent magnet is changed by the modulation of the modulating ring. When $m = 1, k = -1$, the amplitude of the modulated spatial harmonic magnetic field is the largest [6].

In order to make the magnetic field generated by the inner and outer rotor magnetic poles perform stable energy transfer and maximize the torque transmitted by the outer rotor, the number of pairs of outer rotor magnetic poles should be equal to the number of $p_{1,-1}$ modulation harmonic magnetic fields. Therefore, the number of pairs of outer rotor poles should be chosen to be $(n_s - p)$.

When the magnetic flux ring is fixed and the two rotors rotate for torque transmission $\Omega_s = 0$, the transmission ratio of the magnetic field modulated magnetic gear can be determined by the formula (6).

$$G_r = \frac{\Omega_r}{\Omega_{m,k}} = \frac{p - n_s}{p} \tag{6}$$

According to the analytical principle, in order to realize the variable speed movement and the maximum energy transmission of the designed magnetic gear, the number of the magnetic flux ring must be equal to the sum of the pole pairs of the inner and outer rotor permanent magnets.

2.3 Finite element method

The finite element method is not directly dispersed into algebraic equations based on the equation of the field. It requires a conditional variation problem as a medium, that is, the equation of the field is equivalent to a conditional variation problem, and then the conditional variation problem is dispersed, and then the required algebraic equations are obtained. Using the finite element method to solve the electromagnetic field problem, the steps are as follows:

(1) The column writes a conditional variation problem that is equivalent to the boundary value problem of the partial differential equation. Determining the solution of conditional variation problems based on the unique solution of boundary value problem of partial differential equations.

(2) Discretion of conditional variation problems. The entire region to be sought is divided into a plurality of triangular sub-regions, and then a linear interpolation function is constructed in the triangular unit.

(3) According to the extreme value problem of energy functional, it is transformed into the extreme value problem of solving energy function, and the related linear algebraic equations are established. Find a continuous derivable function $\varphi(x, y)$ on the premise that the energy functional $W(\varphi)$ reaches a minimum value.

(4) Solving the established linear algebraic equations.

3. Experiments

The finite element calculation analysis of the dynamic performance of the structural model of the magnetic gear. In the dynamic performance analysis of the magnetic gear, the inner rotor is still selected as the driving wheel, the input speed is 275r/min, the outer rotor is used as the driven wheel, and the starting angle is selected as 30 degrees. Analyze the magnetic gear in the stable operation interval and the unsteady operation interval, that is, the oscillation phenomenon of the internal and external rotor torque and speed under the conditions of no-load start, load start and sudden load disturbance.

4. Analysis and Discuss

4.1 Dynamic Characteristics Analysis of Modulated Magnetic Gears

(1) No-load starting characteristics

The magnetic gear is started at no load, and the simulation results of the front and rear output of the damper winding are added as shown in Figure 1-3. It can be seen from the figure that the rotor torque and the outer rotor rotation speed both exhibit strong oscillation attenuation characteristics at the beginning of the start, and the magnetic gear seriously exhibits low stiffness characteristics during this process.

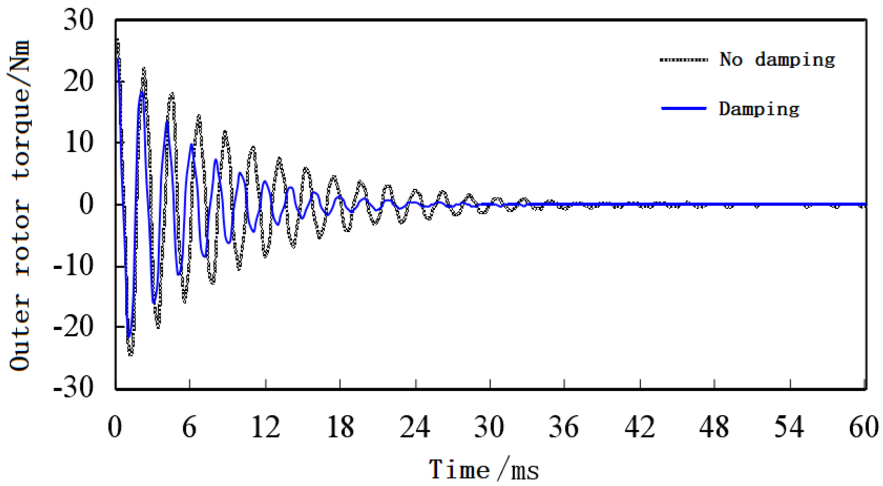

Figure 1. External rotor torque as a function of time

For the external rotor torque, the adjustment time required for the magnetic gear to enter steady state operation when the damper winding is not applied reaches 34.6 ms. After the damper winding is added, the adjustment time is 21.6 ms.

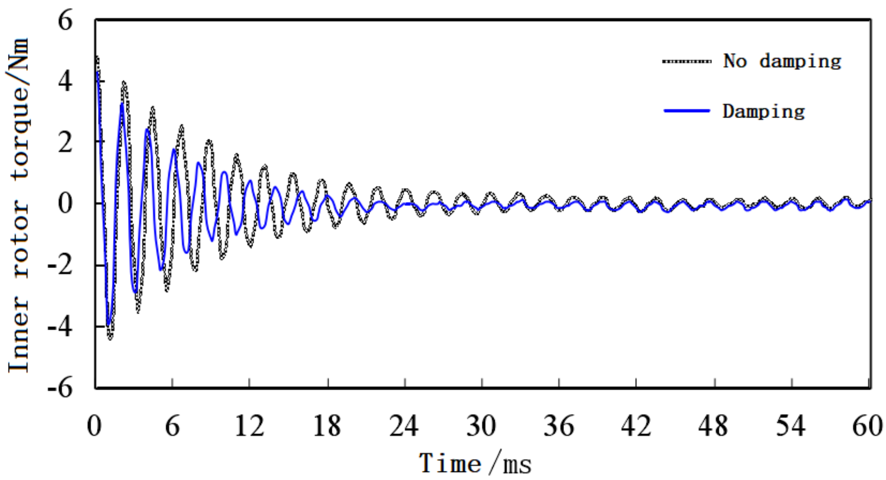

Figure 2. Internal rotor torque as a function of time

The phenomenon of internal rotor torque oscillation is similar to the external rotor torque ripple.

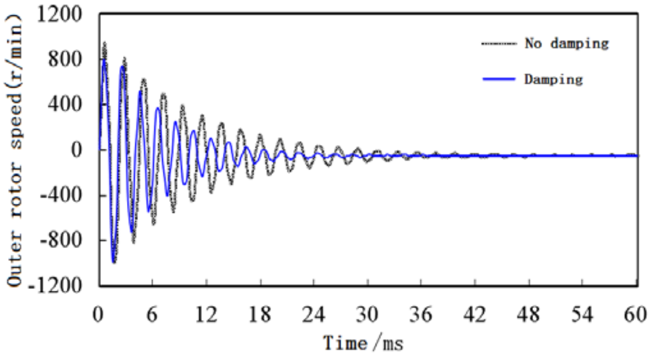

Figure 3. External rotor speed as a function of time

The output speed changes with the oscillation of the torque. Before the damper winding is added, the adjustment time of the outer rotor speed is 33.2 ms, which is 22.0 ms after the addition. After entering the steady state, the speed is maintained at -50r/min, which meets the transmission ratio requirements. The negative sign indicates the opposite direction of rotation of the inner rotor.

With the addition of the damper winding, the amplitude of the oscillation of the torque and the rotational speed of the magnetic gear is reduced at the start-up, and the steady-state time is significantly shortened, which reduces the influence of the oscillation at the starting moment on the system.

(2) Load start characteristics

When the no-load start, the internal rotor input speed, simulation time and step length are unchanged. After the load is increased by 20Nm, the magnetic gear load start change process is observed. The simulation results are shown in Figure 4-6.

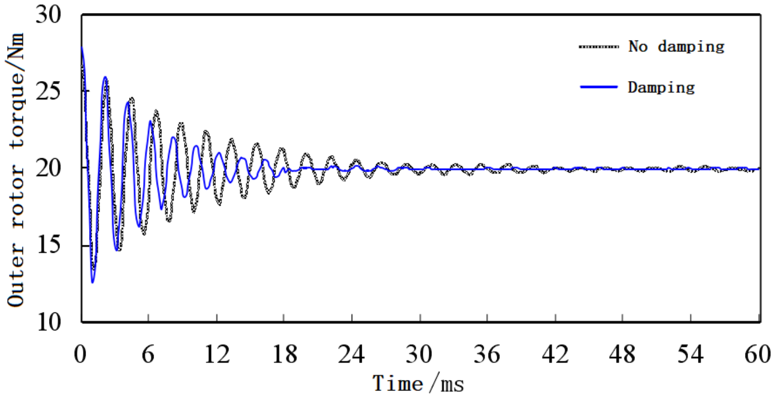

Figure 4 External rotor torque as a function of time

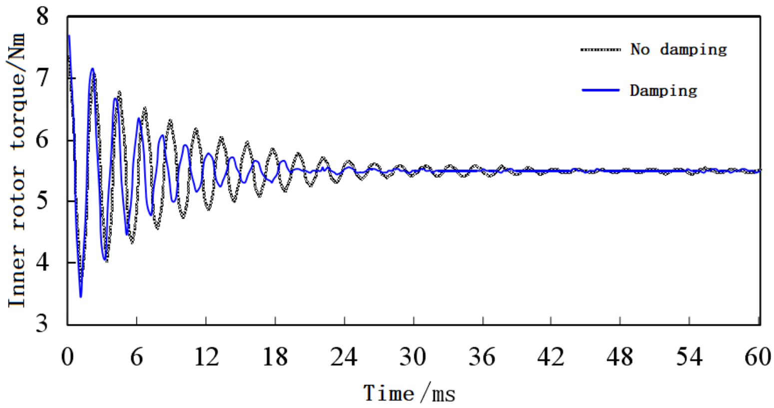

Figure 5. Internal rotor torque as a function of time

From Fig 4 and Fig 5, at the beginning of the load start, the internal and external rotor torque ripples appear similar to the step response of the no damped second-order system. The adjustment time of the outer rotor torque before adding the damper winding is 29.6 ms, which is 17.0 ms after the damping is added. The overshoot is 35% when the damper winding is not applied. The oscillation trend of internal and external rotor torque is basically the same. After entering the steady state, the inner and outer rotor torques are respectively stabilized at the average value of 20Nm and 3.6Nm, and are balanced with the load torque, which also conforms to the change of the transmission ratio.

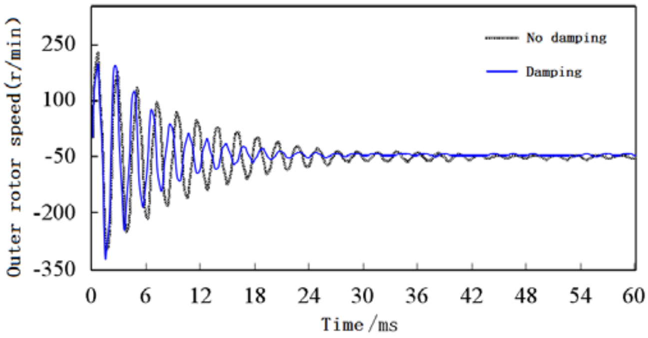

Figure 6. External rotor speed as a function of time

Figure 6 shows the adjustment time of the outer rotor output speed before adding the damper winding to 35.6ms and 20.6ms after the addition.

After the inner rotor increases the damper winding, the amplitude of the internal and external rotor pulsating torque of the magnetic gear decreases, and the overshoot decreases. Compared with the no damped winding, the adjustment time is obviously shortened, and the stable operation state is advanced in advance, and the dynamic stability of the entire transmission system can be improved.

(3) Sudden load characteristics

The magnetic gear starts at no load and waits for it to reach stable operation. Then, the load torque is 20Nm at t=75ms, and the internal and external rotor torque and outer rotor speed change curves are shown in Figure 7-9.

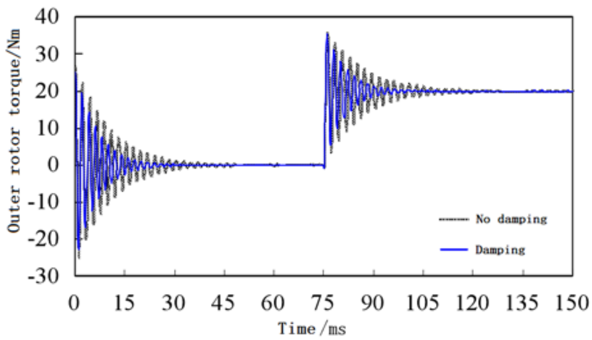

Figure 7. External rotor torque as a function of time

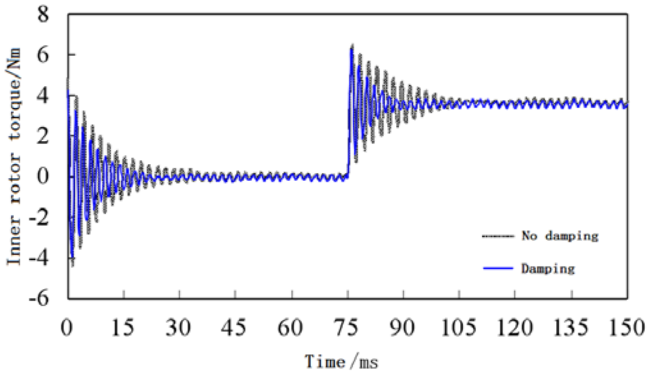

Figure 8. Internal rotor torque as a function of time

It can be seen from Figures 7 and 8 that when the magnetic gear is disturbed by the sudden load, the internal and external torques immediately exhibit torque ripple, and the oscillation phenomenon is similar to the change of the starting torque. Before the increase of the damper winding, the adjustment time of the outer rotor torque was measured to be 35.0 ms, and the adjustment time of the inner rotor torque was 34.2 ms. After the damper winding is added, the adjustment time of the outer rotor torque is 19.8 ms, and the adjustment time of the inner rotor torque is 15.2 ms. The adjustment time of the inner rotor torque was reduced by 43.4%, and the adjustment time of the outer rotor torque was reduced by 55.5%.

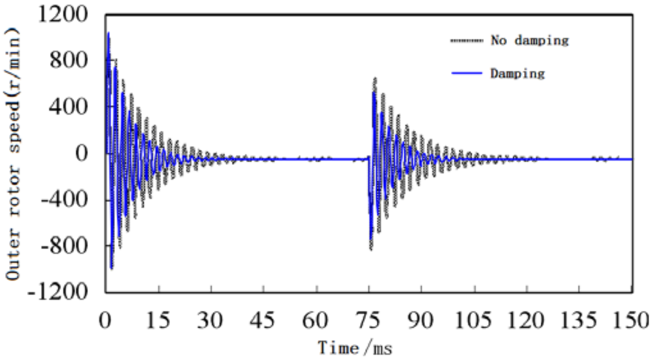

Figure 9. External rotor speed as a function of time

After the magnetic gear that has been running stably after the no-load start oscillation has been subjected to the sudden disturbance, the output speed of the outer rotor also oscillates immediately, as shown in Fig 9. With the generation of damping torque, the adjustment time is reduced by 42.8%, and the oscillation amplitude is also significantly reduced.

After the addition of the damper winding, the adjustment time required for the magnetic gear to be disturbed to re-enter into the steady state is significantly reduced. The generation of the damping torque also reduces the strength of the rotational speed pulsation. The rotor torque and speed are finally stabilized at their respective equilibrium positions and operate in a manner consistent with the gear ratio.

4.2 Optimization Analysis of Damper Winding

From the above analysis of the dynamic characteristics of the magnetic gear, it can be known that the addition of the damper winding reduces the vibration amplitude and adjustment time of the magnetic gear and improves the dynamic stability of the system. However, the number of damping bars, the resistance value, and the resistance value of the end ring connecting the damping bars affect the generation of damping torque.

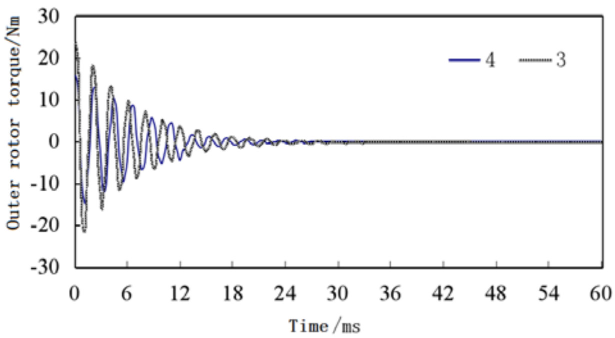

Figure 10. Influence of Different Damping Numbers on Torque Fluctuation

In the magnetic gear with the damper winding, the number of dampers is set to 3 and 4 under the permanent magnet of each inner rotor, and the other parameters are unchanged. When the magnetic gear is started at no load, it can be seen from Fig. 10 that the adjustment time required for the low-speed outer rotor torque as the driven wheel to enter the stable operating state from the oscillation is 21.6 ms and 18.2 ms. Theoretically, the damping torque will increase as the number of damping bars increases, so that the oscillation amplitude of the magnetic gear is smaller when the magnetic gear is disturbed, and the adjustment time is shorter. In fact, the number of damping bars placed at each pole of the magnetic gear is not limited by the size of the structure. And since the magnetic permeability of the damper winding is approximately equal to the air permeability, the excessive number of dampers will hinder the rotor flux from providing effective torque transmission. Therefore, the size of the inner rotor permanent magnet and the size of the salient pole should be considered without affecting the maximum transmission torque, and the number of damping bars should be reasonably selected.

5. Conclusion

With the continuous development and wide application of magnetic gears, the performance requirements of magnetic gear are also getting higher. In this paper, the research and analysis of the proposed magnetic gear with damper winding, although achieved certain results, still have great potential for exploration. For example, when optimizing the structural parameters of the magnetic gear in the paper, only several parameters that have a major influence on the performance of the magnetic gear are optimized. The parameter selection is discrete, so the obtained model parameter value is not necessarily the optimal solution. The addition of the damper winding successfully suppresses the transient oscillation of the magnetic gear and improves the dynamic stability of the system. The addition of the damper winding will inevitably increase the loss. However, the loss of the magnetic gear is not further analyzed. Reducing losses is also one of the problems that need to be solved.

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