

Article

Analysis and Performance Evaluation of a Novel Adjustable Speed Drive with a Homopolar-Type Rotor

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Abstract: The use of a magnetic adjustable speed drive is a popular choice in industrial settings due to its efficient operation, vibration isolation, low maintenance, and overload protection. Most conventional magnetic adjustable speed drives use various forms of the permanent magnets (PMs). Due to the PMs, this type of machine has continuous free-wheeling losses in the form of hysteresis and induced eddy currents. In recent years, the homopolar-type rotor has been widely used in high-speed machines, superconducting machines, and in the application of flywheel energy storage. This study proposes a new application of the homopolar-type rotor. A novel adjustable speed drive with a homopolar-type rotor (HTR-ASD), which has obvious advantages (no brush, no permanent magnet, and no mechanical flux regulation device), is designed and analyzed in this study. Its speed and torque can be adjusted only by adjusting the excitation current. Firstly, in this study, the structure, operation principles, and flux-modulated mechanism of the HTR-ASD are studied. The homopolar-type rotor has a special three-dimensional magnetic circuit structure with the same pole. The 3D-FEM is usually used to calculate its parameters, which is time consuming. In this study, an analytical method is developed to solve this issue. To analytically calculate the torque characteristics, the air gap magnetic flux density, and the winding inductance parameter, the equivalent circuit and the air gap permeance are researched to simplify the analysis. Then, the key parameters of the HTR-ASD are calculated. Finally, the performance of the HTR-ASD is comparatively studied using the analytical method and finite element method, and a comparison of the results is carried out. The comparison indicates that the analytical method is in good agreement with simulation results, and that it is very helpful for designing homopolar-type rotor machines. According to the analysis, the proposed adjustable speed drive displays a great performance in relation to the operating characteristics of a flexible mechanical speed drive.



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MSC: 00A06

1. Introduction

Mechanical coupling adopts a rigid structure, which is simple, reliable and low cost. However, it requires a high alignment accuracy between the power input end and load end during installation. Meanwhile, it cannot isolate harmful vibrations and has no overload protection function [1]. That means the use of a solid medium to transmit power cannot solve the inherent problems of harmful vibration isolation and overload protection at the input and output ends. Figure 1 shows a damaged rotating shaft and bearing due to shafting vibration.

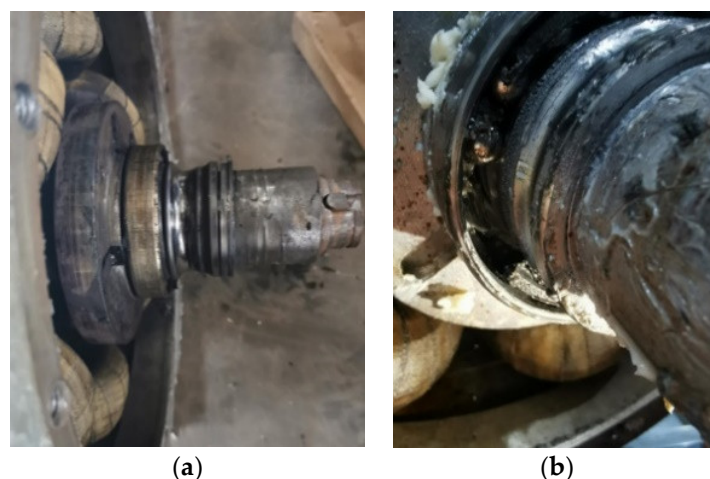


Figure 1. A damaged rotating shaft and bearing due to shafting vibration. (a) The damaged rotating shaft. (b) The damaged bearing.

Compared with mechanical coupling, magnetic adjustable speed drives have attracted a great deal of attention. As the electromagnetic field is used as the power transmission medium, the transmission link has no direct mechanical contact, leading to complete isolation between the power drive end and the load end, which perfectly solves many problems such as the isolation of harmful vibrations, overload protection, motor safety starting with loads, etc. [2–4].

At present, most of the existing magnetic adjustable speed drives contain permanent magnets, and speed adjustment is mainly achieved through the non-rotary mechanical speed regulation structure to adjust the air gap length [5,6]. For permanent magnet adjustable speed drives, because they contain permanent magnets, this type of machine has continuous free-wheeling losses in the form of hysteresis and induced eddy currents, which may lead to high-temperature loss of excitation and vibration loss of excitation. Additionally, because they contain a mechanical speed regulation structure, this also increases the complexity and reduces the reliability of the system.

The homopolar-type rotor is very simple and robust, and has been widely used in high-speed ac machines [7]. In some conditions, it can have a similar performance to the typically used PM machines [8]. For this reason, researchers have paid much attention to this type of machine. The authors of [9] use a bearingless ac homopolar alternator for a flywheel energy storage system, which avoids significant mechanical friction, increases the motor efficiency and increases the operational lifespan. The authors of [10] use a novel permanent magnet homopolar inductor machine with a mechanical flux modulator for a flywheel energy storage system. The authors of [11] use this type of rotor for a bearingless motor, which can be driven up to an ultrahigh speed of 100,000 r/min. The authors of [12] use a homopolar motor in a mining truck with a carrying capacity of 90 tons.

In addition to the above application, this study proposes a new application of the homopolar-type rotor that could be used to regulate the speed of the load, named the homopolar-type rotor adjustable speed drive (HTR-ASD). It usually contains a homopolar-type rotor, a squirrel-cage rotor and a non-rotary shell with an excitation winding. This machine has no brush, no permanent magnet, and no mechanical flux regulation device. At the same time, the rotating parts of the device are composed of a solid homopolar-type rotor and a simple squirrel cage structure, making it fit for high-speed or high-temperature occasions [13,14]. Its magnetic excitation is produced by a dc current in a stationary field with the winding fixed to the shell. In the regulation process, the speed and torque can be adjusted only by adjusting the amplitude of excitation current. This current can be completely turned off during idling times to eliminate magnetic losses.

The performance of the adjustable speed drive may be studied by either numerical or analytical approaches [2]. The former, such as the finite element method (FEM), albeit

precise, are time consuming. To simplify the analysis of magnetic adjustable speed drives, some researchers use an analytical method. The analytical methods mainly include the field analysis analytical model and the magnetic equivalent circuit (MEC) model. The field analysis analytical model is based on Maxwell's equations and boundary conditions. The MEC is a simple analytical calculation method [15,16]. In recent years, it has been applied in the design of eddy current couplings [17] and retarders [18,19]. The authors of [20] use an analytical method to calculate the torque characteristics of a novel hybrid superconducting magnetic coupling with axial flux. The authors of [21,22] attempt to simplify the actual 3D geometric model as a 2D model for research, aiming to increase the efficiency of the preliminary design. However, most of the analyses are for the PM adjustable speed drive and are not suitable for the adjustable speed drive proposed in this study.

The homopolar-type rotor has a three-dimensional magnetic circuit structure with the same pole and the 3D-FEM is often used for its analysis [23]. The use of the 3D-FEM enables an accurate result to be obtained; however, this method is time consuming. Therefore, the 3D-FEM is usually used for the final performance check. To conveniently obtain an effective no-load air gap flux density, a simplified 2D equivalent analysis model of the homopolar machine is proposed by [24]. Through this method, the no-load effective air gap flux density can be calculated. However, whether this method is applicable to the load condition of this machine is not stated. To calculate the load condition of this type of machine, the authors of [25] adopted a 2D simplified analysis method for a PM homopolar inductor machine. However, this model is for PM homopolar machines and is not suitable for electric excitation machines. Aiming to simplify the calculation of a 3D magnetic circuit for this type of machine, some researchers have used MEC [26,27]. As for the parameter calculations, the authors of [27] use the rotor shape function to speed up the calculation and analysis process. However, the authors of [27] ignore the difference between the rotor shape and the air gap permeance, so the corresponding conclusion is not accurate enough.

In this study, an analytical examination of the homopolar-type rotor is performed, which is found to be effective in the preliminary design stages and analysis of electric machines. To analyze the speed regulation characteristics, the equivalent circuit of the HTR-ASD is obtained and the torque of this machine is calculated by using it. The air gap permeance function is analyzed, which is used not only for analyzing the air gap magnetic field parameters, but also for calculating the winging parameters. The air gap permeance function in this study is directly related to the rotor shape, which means that it is much more accurate than in [27]. By using the analytical method proposed in this study, researchers can quickly obtain the primary scheme of the machine and evaluate its performance [28–30].

The remainder of this paper is organized as follows. In Section 2, the operation principle and the flux-modulated mechanism of the HTR-ASD are analyzed in detail. The equivalent circuit of the HTR-ASD is studied and the torque of the HTR-ASD is calculated in Section 3. Then, the analytical method is proposed and key parameters of the HTR-ASD are calculated. In Section 4, an HTR-ASD prototype is designed and the performances of the HTR-ASD are comparatively studied by the analytical method and the finite element method. The comparison of the results shows the accuracy of the analytical method, indicating that the proposed adjustable speed drive can be applied successfully.

2. Structure and Operation Principles

2.1. Structure

A three-dimensional view of the proposed HTR-ASD is shown in Figure 2. It is composed of a homopolar-type rotor, a squirrel-cage rotor and a non-rotary shell with an excitation winding. The squirrel-cage core is formed by laminated silicon steel sheets and embedded with a squirrel cage whose middle part is composed of non-ferromagnetic material. The homopolar-type rotor is fabricated with high-strength solid steel. The shell and the excitation winding are the non-rotary parts of the machine.

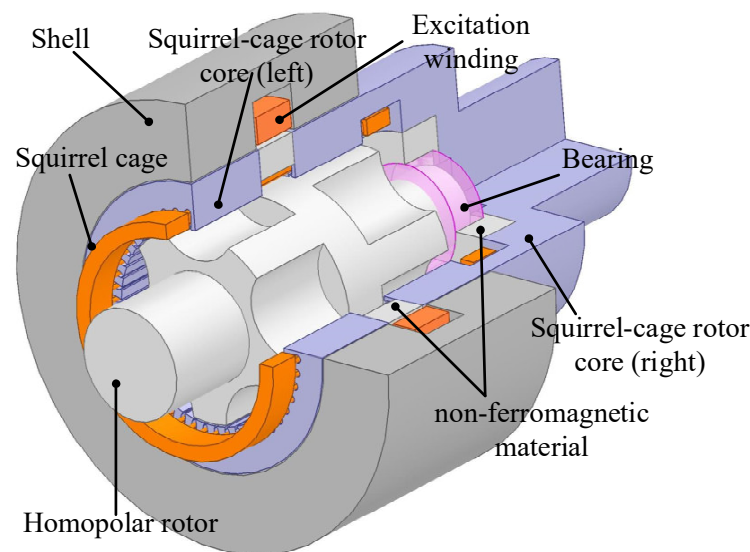


Figure 2. Three-dimensional simplified view of an HTR-ASD.

As Figure 3 shows, the homopolar-type rotor is connected to the prime motor and the squirrel-cage rotor is connected to the load. When the HTR-ASD is working, the torque transmitted by the HTR-ASD is determined by the slip of the homopolar-type rotor and the squirrel-cage rotor, which can be expressed by:

$$s = \frac{n_{HTR} - n_{SCR}}{n_{HTR}} \quad (1)$$

where n_{HTR} is the speed of the homopolar-type rotor and n_{SCR} is the speed of the squirrel-cage rotor. Therefore, when the load torque is certain, the slip can be changed by adjusting the dc excitation current, so that the speed can be adjusted.

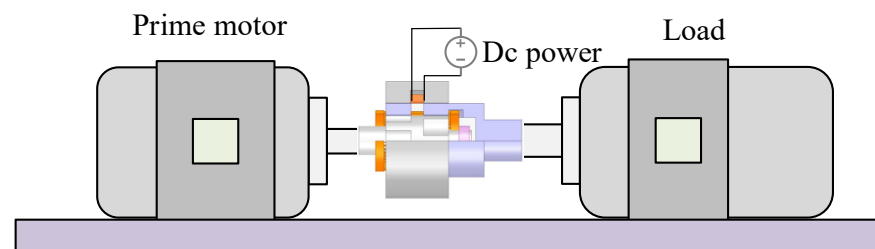


Figure 3. The working platform of the HTR-ASD.

2.2. Operation Principle

The excitation winding provides the flux for the HTR-ASD. The flux is closed through the shell, the air gap between the shell and the squirrel-cage rotor, the squirrel-cage rotor core, the air gap between the squirrel-cage and the HTR, and the HTR, as shown in Figure 4. Additionally, Figure 5 shows that the ac component of air gap flux density is generated due to the different air gap permeances corresponding to the rotor teeth and slots. When the HTR rotates, a synchronous rotating magnetic field is generated in space. The alternating component of the magnetic field generates a corresponding current in the squirrel-cage rotor. The current interacts with the rotating magnetic field in the air gap to generate electromagnetic torque.

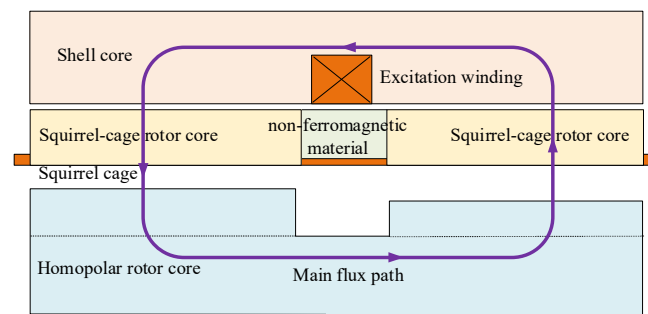


Figure 4. The main flux path in no-load operation.

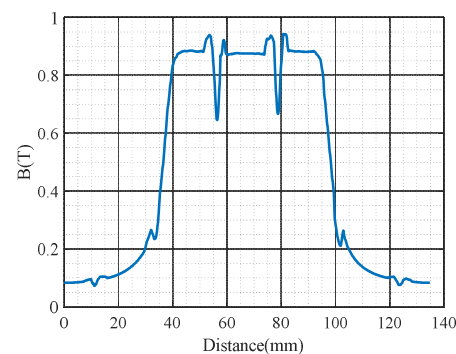


Figure 5. Air gap flux density distributions at different positions of the HTR-ASD.

3. The Equivalent Circuit for Analysis and the Analytical Calculation of Key Parameters

3.1. The Equivalent Circuit for Analysis and the Calculation of Output Torque

Although the winding structure of the squirrel-cage rotor is a squirrel cage type, the winding can still be converted into equivalent three-phase winding to simplify the analysis. Therefore, the equation of the HTR-ASD in the rotor d-q frame can be expressed as:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \\ u_f \end{bmatrix} = p \begin{bmatrix} L_{sd} & 0 & M_{af} \\ 0 & L_{sq} & 0 \\ \frac{3}{2}M_{af} & 0 & L_f \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} + \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_f \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} + \begin{bmatrix} -\omega\psi_{sq} \\ \omega\psi_{sd} \\ 0 \end{bmatrix} \quad (2)$$

where $\omega = \omega_{HTR} - \omega_{SCR}$. ω_{HTR} is the angular velocity of the homopolar-type rotor, and ω_{SCR} is the angular velocity of the squirrel-cage rotor.

To obtain the equivalent circuit, the excitation winding is converted to the squirrel-cage rotor side. The flux linkage equation can be expressed as:

$$\begin{bmatrix} \psi_{sd} \\ \psi'_f \end{bmatrix} = \begin{bmatrix} L_{sd} & L_{md} \\ L_{md} & L'_f \end{bmatrix} \begin{bmatrix} i_{sd} \\ i'_f \end{bmatrix} \quad (3)$$

where $i'_f = \frac{2}{3}i_f M_{af} / L_{md}$.

As the squirrel cage is short circuited, there is $u_{sd} = u_{sq} = 0$. Therefore, the equivalent circuit is as shown in Figure 6.

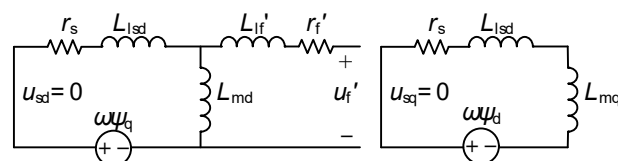


Figure 6. The equivalent circuit of HTR-ASD.

When HTR-ASD operates in steady state, there is:

$$\begin{cases} I_{sq} = -\frac{\omega\psi_{sd}}{r_s} \\ I_{sd} = \frac{\omega\psi_{sq}}{r_s} \end{cases} \quad (4)$$

The electromagnetic torque can be expressed as:

$$T_{em} = 1.5p(\psi_{sd}I_{sq} - \psi_{sq}I_{sd}) = -1.5p\frac{r_s}{\omega}(I_{sq}^2 + I_{sd}^2) \quad (5)$$

Combined with Equations (3) and (4), I_{sd} can be expressed as:

$$I_{sd} = \frac{\omega^2 L_{sq} L_{md} i_f'}{r_s^2 + \omega^2 L_{sq} L_{sd}} \quad (6)$$

The steady-state salient ratio ρ is defined as:

$$\rho = \frac{L_{sq}}{L_{sd}} \quad (7)$$

Combined with Equations (4)–(7), T_{em} can be expressed as:

$$T_{em} = -1.5pr_s i_f'^2 \frac{\omega L_{md}^2 (r_s^2 + \rho^2 \omega^2 L_{sd}^2)}{(r_s^2 + \rho \omega^2 L_{sd}^2)^2} \quad (8)$$

When $\rho = 1$, T_{em} can be expressed as:

$$T_{em} = -\frac{2}{3}pr_s i_f'^2 \frac{M_{af}^2}{r_s^2 + \omega L_{sd}^2} \quad (9)$$

From Equations (7)–(9), it can be seen the torque of the HTR-ASD is related to the excitation current and slip speed. When the excitation current is constant, its torque characteristics are similar to an asynchronous motor. When the load torque is constant, the speed can be adjusted by changing the excitation current. Generally, the difference between L_{sq} and L_{sd} is not too large, and Equation (9) can be used to reflect the torque of the HTR-ASD for simplifying the calculations.

3.2. Calculation of Air Gap Magnetic Field Parameters

Strictly speaking, because the homopolar-type rotor has a special three-dimensional magnetic circuit structure with the same pole, it is necessary to develop a 3D-FEM to accurately calculate its parameters. Nevertheless, since this method requires huge computation time, it is usually used for the final performance check of the design and is not suitable for analytical research and calculations.

To simplify the calculation, the air gap performance function can be considered. The authors of [27] use the rotor shape function to represent the air gap performance function. However, according to the hypothesis of the equal magnetic potential plane, the air gap magnetic field is perpendicular to the rotor surface. Figure 7a shows the axial view of the HTR-ASD, and Figure 7b shows the no-load magnetic density distribution within one rotor tooth pitch. Obviously, the air gap magnetic density waveform is very different from the rotor slot shape.

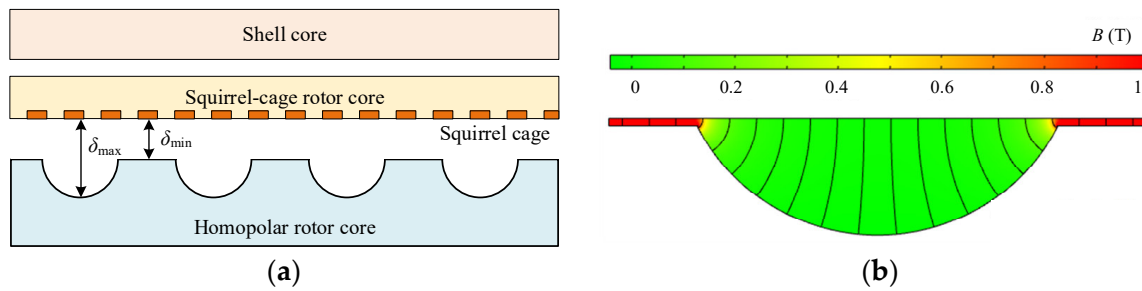


Figure 7. The axial view of the HTR-ASD and no-load magnetic density distribution within one rotor tooth pitch. (a) The axial view of the HTR-ASD. (b) No-load magnetic density distribution within one rotor tooth pitch.

Before analyzing the composite magnetic flux density, it is necessary to analyze the waveform of single-side air gap magnetic flux density. Figure 8 shows the air gap permeance waveform and its components. To calculate different slot shapes, the per-unit values of the air gap performance function λ_n^* are adopted. $\lambda^*(\theta)$ is multiplied by the reference value Λ_B to obtain the actual value, in which the reference value of specific permeability can be expressed by:

$$\Lambda_B = \mu_0 / (k_\delta \delta_{\min}) \quad (10)$$

where μ_0 and k_δ denote the vacuum permeability and Carter's coefficient of slotting, respectively.

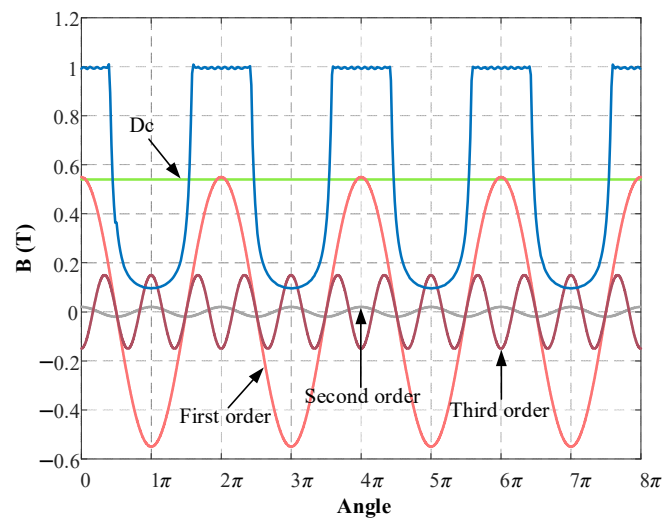


Figure 8. Air gap rate permeance waveform and each component.

The definition of the per-unit air gap permeance function is:

$$\lambda_\delta^*(\theta) = \frac{B(\theta)}{\Lambda_B F_\delta} = \sum_{n=0}^{\infty} \lambda_n \cos n\theta \quad (11)$$

where F_δ is the magnetomotive force (MMF) of the air gap.

The air gap magnetic density on both sides during no-load excitation can be expressed as:

$$\begin{cases} B_{dcl} = F_{F\delta} \sum_{n=0}^{\infty} \lambda_n \cos n\theta \\ B_{dcr} = F_{F\delta} \sum_{n=0}^{\infty} (-1)^{n+1} \lambda_n \cos n\theta \end{cases} \quad (12)$$

The per-unit value of the dc air gap permeance function can be expressed as:

$$\lambda_{dc}^*(\theta) = \frac{B_{dcl} + B_{dcr}}{F_{F\delta}\Lambda_B} = 2 \sum_{n=0}^{\infty(\text{odd})} \lambda_n \cos n\theta \quad (13)$$

The amplitudes of armature winding MMF on the d-axis and q-axis can be expressed as:

$$\begin{cases} F_{ad} = F_{1m} \cos \theta_1 \\ F_{aq} = F_{1m} \sin \theta_1 \end{cases} \quad (14)$$

The d-axis and q-axis components of air gap magnetic density on the left and right sides caused by armature reaction can be expressed as:

$$\begin{cases} B_{dl} = k_{dm} F_{1m} \cos \theta_1 \sum_{n=0}^{\infty} \lambda_n \cos n\theta \\ B_{dr} = k_{dm} F_{1m} \cos \theta_1 \sum_{n=0}^{\infty} (-1)^{n+1} \lambda_n \cos n\theta \end{cases} \quad (15)$$

$$\begin{cases} B_{ql} = k_{qm} F_{1m} \sin \theta_1 \sum_{n=0}^{\infty} \lambda_n \cos n\theta \\ B_{qr} = k_{qm} F_{1m} \sin \theta_1 \sum_{n=0}^{\infty} (-1)^n \lambda_n \cos n\theta \end{cases} \quad (16)$$

where k_{dm} and k_{qm} represent the proportion of air gap MMF in parallel d-axis and q-axis magnetic circuits on both sides.

The per unit values of the d-axis and q-axis air gap permeance functions can be expressed as:

$$\lambda_d^*(\theta) = \frac{B_{dl} + B_{dr}}{k_{dm} F_{1m} \Lambda_B} = (2\lambda_0 + \lambda_2) \cos \theta + \sum_{n=3}^{\infty(\text{odd})} (\lambda_{n-1} + \lambda_{n+1}) \cos n\theta \quad (17)$$

$$\lambda_q^*(\theta) = \frac{B_{ql} + B_{qr}}{k_{qm} F_{1m} \Lambda_B} = (2\lambda_0 - \lambda_2) \sin \theta + \sum_{n=3}^{\infty(\text{odd})} (\lambda_{n-1} - \lambda_{n+1}) \sin n\theta \quad (18)$$

Therefore, $\lambda_{dc}^*(\theta)$, $\lambda_d^*(\theta)$, and $\lambda_q^*(\theta)$ can be regarded as a bridge between the rotor shape and the machine parameters. When the rotor shape is determined, their values can be obtained from a look-up table [31]. After that, they can be used to analytically calculate the air gap magnetic flux density and the winding inductance parameter.

3.3. Calculation of Excitation Winding Parameters

Another parameter to be calculated is the excitation time constant, which is closely related to the resistance and inductance of the excitation winding. Figure 9 shows the excitation window and its size, which is used for the assembly of excitation windings.

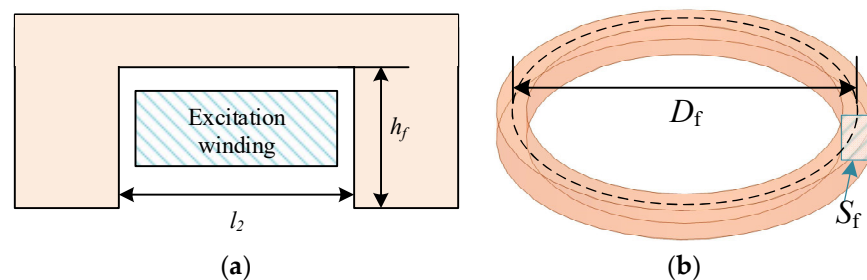


Figure 9. Excitation window and excitation winding. (a) Excitation window and its size. (b) Excitation winding.

The resistance of the excitation winding can be expressed as:

$$r_f = \frac{\rho_{Cu} N_f \pi D_f}{S_{cf}} \quad (19)$$

where ρ_{Cu} is the conductivity of copper, N_f is the turn of excitation winding, D_f is the excitation coil diameter and S_{cf} is the cross-sectional area of the excitation coil.

Under the excitation current alone, the magnetic density of a one-sided air gap between the HTR and the squirrel-cage rotor can be expressed as:

$$B_{dcl}(\theta) = \frac{N_f I_f}{2} k_m \sum_{n=0}^{\infty} \lambda_n \cos n\theta \quad (20)$$

Therefore, the average air gap flux density at one side of the machine can be expressed as:

$$B_{av} = \frac{1}{2\pi} \int_0^{2\pi} B_{dcl}(\theta) d\theta = \frac{N_f I_f}{2} k_m \lambda_{dc0}^* \Lambda_B \quad (21)$$

The main flux linkage of excitation winding is:

$$\psi_{ff} = N_f B_{av} S_\delta = I_f N_f^2 \pi R_H (l_1 + 2\delta) k_m \lambda_{dc0}^* \Lambda_B \quad (22)$$

where S_δ represents the total area of a one-sided air gap between HTR and the squirrel-cage rotor, R_H is the radius of the HTR, and l_1 is the single length of the HTR.

The main inductance of the excitation winding is:

$$L_{ff} = \frac{\psi_{ff}}{I_f} = N_f^2 \pi R_H (l_1 + 2\delta) k_m \lambda_{dc0}^* \Lambda_B \quad (23)$$

Moreover, (23) shows that the main self-inductance of the excitation winding only contains the dc component, because in the same pole magnetic field structure, the self-inductance parameters of the excitation winding are determined by the overall magnetic circuit state and have nothing to do with the details of the air gap flux density waveform.

The excitation time constant can be expressed by:

$$t_f = \frac{L_{ff}}{r_f} = \frac{N_f \pi R_H (l_1 + 2\delta) k_m \lambda_{dc0}^* \Lambda_B}{\rho_{Cu} \pi D_f} S_{cf} \quad (24)$$

In the design of an HTR-ASD, the excitation winding time constant t_f is expected to be as small as possible. On the one hand, it can reduce the excitation establishment time and improve the system mobility. On the other hand, it can make it easier to adjust the flux linkage of the excitation winding in the process of speed regulation, in order to strengthen the dynamic response ability of the system in the process of speed regulation.

3.4. Calculation of Armature Winding Parameters

By using $\lambda_d^*(\theta)$ and $\lambda_q^*(\theta)$, the armature winding parameters can be easily obtained. L_{md} and L_{mq} can be expressed as:

$$L_{md} = \frac{2m\mu_0 D_i (l + 2\delta) k_{dm}}{\delta k_\delta \pi} \left(\frac{NK_{N1}}{p} \right)^2 \lambda_{d1}^*(\theta) \quad (25)$$

$$L_{mq} = \frac{2m\mu_0 D_i (l + 2\delta) k_{qm}}{\delta k_\delta \pi} \left(\frac{NK_{N1}}{p} \right)^2 \lambda_{q1}^*(\theta) \quad (26)$$

where D_i is the inner diameter of the squirrel-cage rotor and l is the length of a single side core. $\lambda_{d1}^*(\theta)$ and $\lambda_{q1}^*(\theta)$ are the fundamental components of $\lambda_d^*(\theta)$ and $\lambda_q^*(\theta)$.

The steady-state salient ratio ρ can be expressed as:

$$\rho = \frac{L_{la} + L_{sq}}{L_{la} + L_{sd}} \quad (27)$$

According to Equations (11) and (12), under no-load excitation, the composite magnetic density of armature winding cutting can be expressed as:

$$B_{dc}(\theta) = \frac{N_f I_f}{2} k_m \lambda_{dc}^*(\theta) \Lambda_B \quad (28)$$

Therefore, the fundamental component of mutual inductance between excitation winding and armature winding can be expressed as:

$$M_{af} = \frac{\mu_0 D_i (l + 2\delta) \lambda_1^*}{\delta k_\delta} \frac{NK_{N1}}{p} N_f \quad (29)$$

From the calculations of the above parameters, it can be clearly seen that by using $\lambda_{dc}^*(\theta)$, $\lambda_d^*(\theta)$, and $\lambda_q^*(\theta)$, the design flow becomes more efficient. As for the calculation of leaked inductance, it is the same as that of a conventional machine. Furthermore, because the winding in the conductor rotor core is a squirrel cage type, the end ring parameters need to be considered [32].

3.5. Magnetic Circuit Calculation

To consider the influence of different position saturation on the calculation of the inductance parameters, the magnetic circuit of the HTR-ASD needs to be calculated. Considering that the surfaces of each part of the HTR-ASD are equimagnetic potential surfaces, the calculation can be simplified using Carter's coefficient. Figure 10 shows the calculation model of the homopolar-type rotor obtained by Carter's factor.

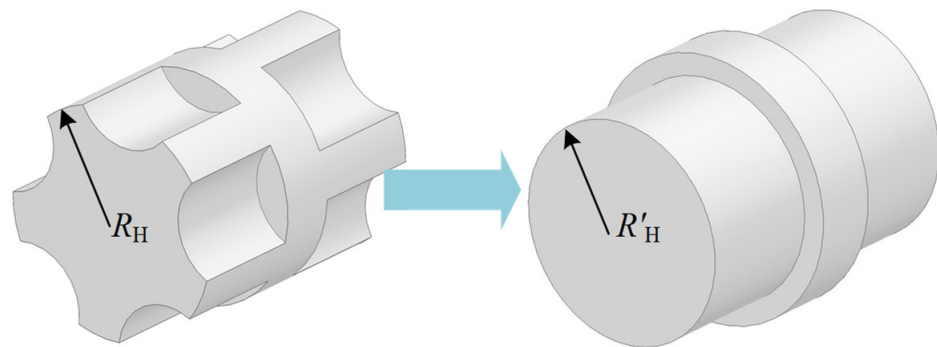


Figure 10. The key parameters and magnetic equivalent circuit of the HTR-ASD.

Figure 11a shows the key parameters of the machine and Figure 11b shows the MEC of the calculation. δl_1 can be written as:

$$\delta l_1 = \delta_{\min} k_{\delta HTR} k_{\delta SCR} \quad (30)$$

where $k_{\delta HTR}$ and $k_{\delta SCR}$ are the Carter coefficients of the homopolar-type rotor and the squirrel-cage rotor.

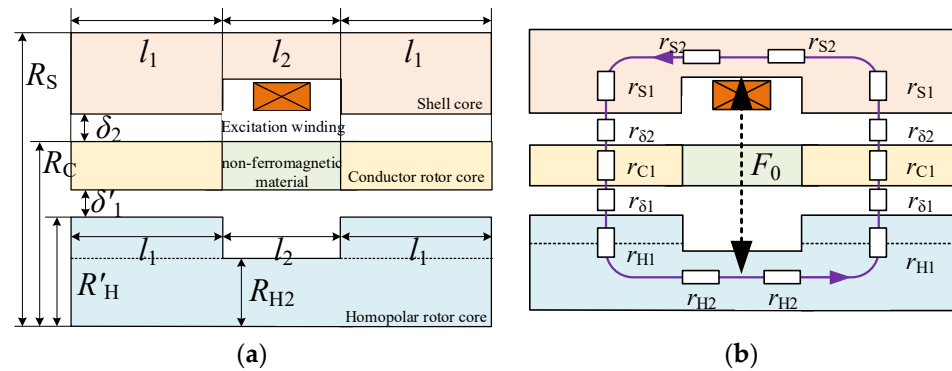


Figure 11. The key parameters and magnetic equivalent circuit of the HTR-ASD. (a) The key parameters of the machine. (b) The MEC of the calculation.

Therefore, the reluctances can be expressed as:

$$\begin{cases} r_{S1} = \frac{\ln(R_S / (R_C + \delta_2))}{2\mu_s \pi l_1} \\ r_{S2} = \frac{l_2}{2\mu_s \pi (R_S - R_C - \delta_2 - h_f)^2} \\ r_{\delta 2} = \frac{\ln(1 + \delta_2 / R_C)}{2\mu_0 \pi l_1} \\ r_{\delta 1} = \frac{\ln(1 + \delta_1' / R_H)}{2\mu_0 \pi l_1} \\ r_{C1} = \frac{\ln(1 + \delta_1' / R_H')}{2\mu_C \pi l_1} \\ r_{H1} = \frac{\ln(R_H' / R_{H2})}{2\mu_H \pi l_1} \\ r_{H2} = \frac{l_2}{2\mu_H \pi R_{H2}^2} \end{cases} \quad (31)$$

The use of a MEC can simplify the calculation of a 3D magnetic circuit and speed up the calculation and analysis processes. At the same time, the air gap magnetic density can be determined by $\lambda_{dc}^*(\theta)$ after calculating the no-load magnetic circuit.

3.6. Summary of the Analysis and Design Method of the HTR-ASD

The above analysis can be summarized as follows:

- (1) When the torque and speed requirements are determined, the key parameters of an HTR-ASD can be obtained using the equivalent circuit and expression (9).
- (2) When the key parameters, like L_{sq} and L_{sd} , are determined, the rotor shape and the winding parameters can be determined by $\lambda_{dc}^*(\theta)$, $\lambda_a^*(\theta)$, $\lambda_q^*(\theta)$, and expressions (25) and (26).
- (3) To consider the influence of different position saturation on the calculation of inductance parameters, a MEC can be used. By using expression (31), the influence of different position saturation on the calculation of inductance parameters can be taken into consideration.
- (4) As for the dynamic characteristics of the HTR-ASD, the s-function simulation model can be established based on expressions (2) and (3).

4. Performance Analysis

4.1. Prototype Design and FEM Analysis

To verify the accuracy of the above analysis and study the characteristics of the machine, a prototype is designed and its parameters are illustrated in Table 1.

Table 1. The parameters of the HTR-ASD.

Parameter	Value	Unit
Pole-pair numbers of the HTR	5	-
The slot numbers of the squirrel-cage rotor	48	-
Air gap length between the squirrel cage and the HTR	1	mm
Air gap length between the squirrel cage and the shell	1	mm
The diameter of the HTR	120	mm
The inner diameter of the shell	182	mm
The length of the shaft	30	mm
Total length	150	mm
The turns of excitation winding	400	-

A 3D finite element model was established to calculate the electromagnetic parameters. Figure 12 shows the 3D-FEM model and the mesh of the rotor finite element model. Figure 13 shows the no-load magnetic field distribution of the axial and radial views at an excitation current of 6A.

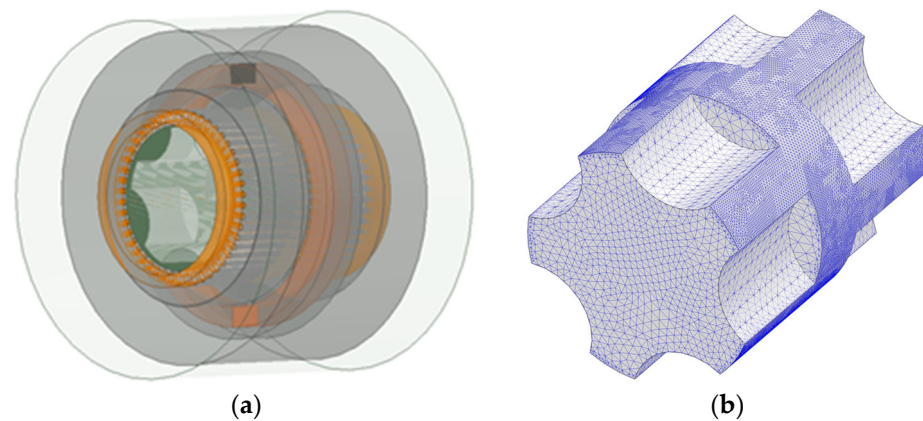
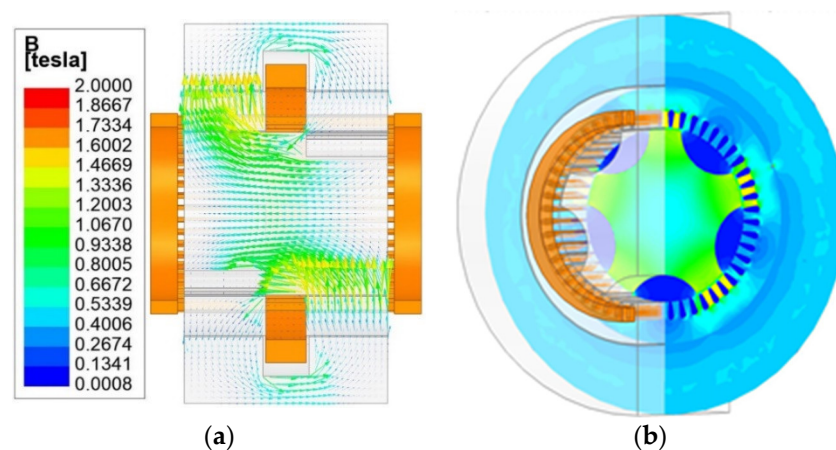
**Figure 12.** Three-dimensional FEM of the HTR-ASD. (a) The FEM model of the HTR-ASD. (b) Mesh of the rotor finite element model.**Figure 13.** No-load magnetic field distribution of the axial and radial views. (a) The no-load magnetic field distribution of the axial view. (b) The no-load magnetic field distribution of the radial view.

Figure 14 shows a comparison between the analytical calculations and the simulation of no-load air gap flux density distribution. This shows that the proposed air gap permeance function and the MEC model of the HTR-ASD are accurate and can be used to calculate the magnetic field of the machine. Figure 15 shows the air gap flux density distribution at different slip speeds and an excitation current of 6A. Additionally, Figure 16 shows

the squirrel-cage current density distribution at different slip speeds and an excitation current of 6A.

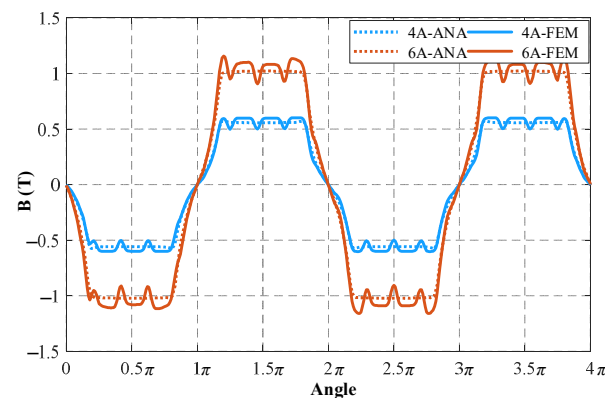


Figure 14. No-load magnetic field distribution of the axial and radial views.

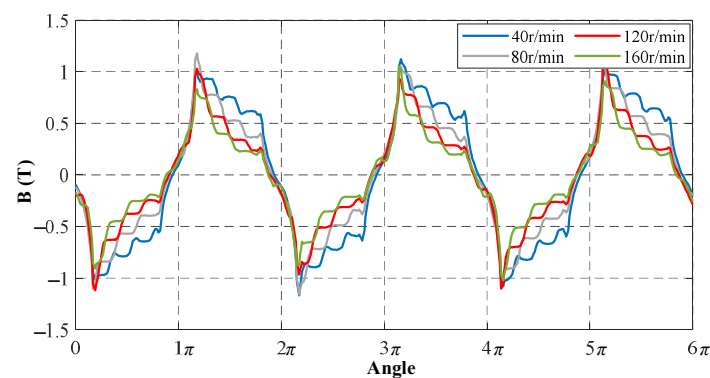


Figure 15. Air-gap flux density distribution under different slip speed at 6A excitation current.

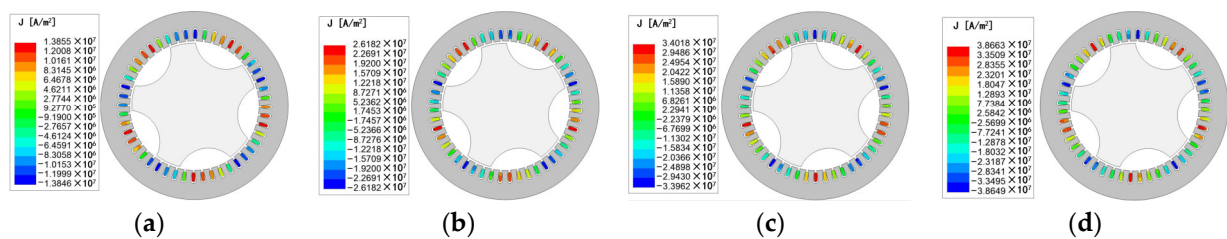


Figure 16. Current density distribution under different slip speeds and an excitation current of 6A. (a) Slip speed = 40 r/min; (b) slip speed = 80 r/min; (c) slip speed = 120 r/min; (d) slip speed = 160 r/min.

4.2. Speed Regulation Characteristics

Figure 17 shows the output torque of the HTR-ASD under different slip speeds and excitation currents. From Figure 17, it can be clearly seen that the speed and torque of the HTR-ASD can be easily adjusted by changing the excitation current. Additionally, the output torque is proportional to the square of the current, which is similar to the characteristics of the voltage regulated speed control of an asynchronous motor. Through a comparison between the analytical calculations and simulations, the accuracy of the analytical analysis in this study is verified. Figure 18 shows the operating characteristics at different prime mover speeds. When the speed of the prime mover changes, its characteristics are like those of the variable frequency speed regulation of an asynchronous motor.

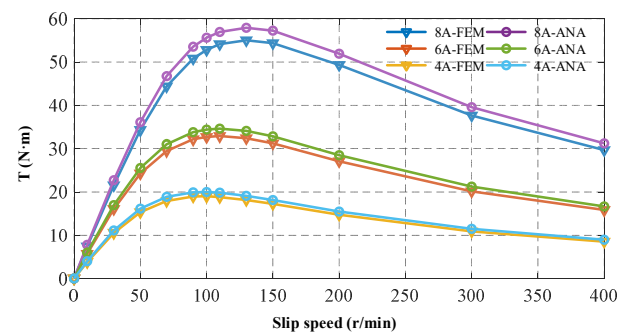


Figure 17. The output torque of HTR-ASD under different slip speed and excitation currents.

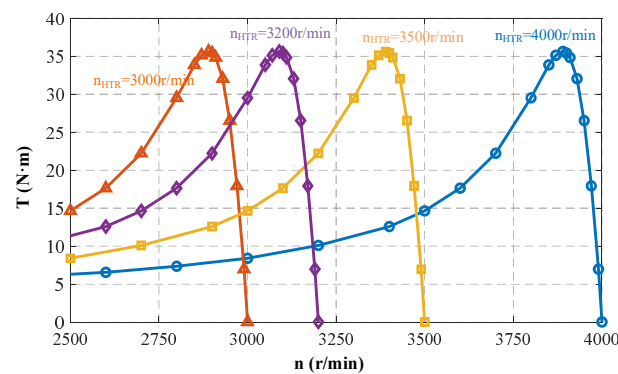


Figure 18. The mechanical properties of the HTR-ASD.

When the inductance parameters of the machine are calculated, the transient torque response of the HTR-ASD can be obtained by the s-function simulation model, which is much quicker than the FEM. Figure 19 shows the transient torque response of the HTR-ASD calculated by the two methods under different slip speeds and an excitation current of 6A. As can be seen from Figure 19, the results of the two methods are basically consistent. Furthermore, the higher the slip speed, the longer the response time because of the larger current.

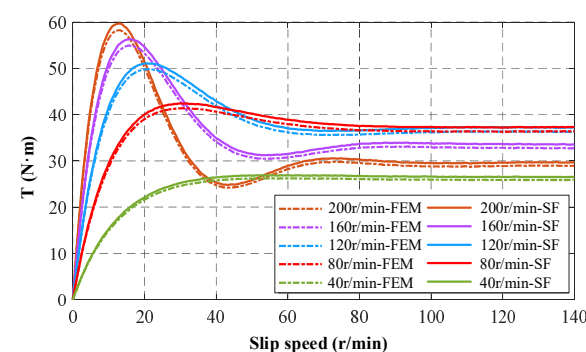


Figure 19. Transient torque response of the HTR-ASD under different slip speeds and an excitation current of 6A.

5. Conclusions

In this study, a new type of adjustable speed drive, named the HTR-ASD, is proposed. Its unilateral air gap magnetic field is unipolar, while its synthetic air gap magnetic field is bipolar. The HTR-ASD has an absence of brushes, permanent magnets, and mechanical flux regulation devices, leading to an obvious advantage of high reliability. The speed and torque can be adjusted only by adjusting the excitation current with dc power. Meanwhile, the rotating parts of the device are composed of a solid homopolar-type rotor and simple

squirrel-cage structure. This simple and robust structure makes it more suitable for working in harsh environments. In order to calculate its steady and dynamic characteristics, the equation and equivalent circuit of the HTR-ASD are analyzed in a rotor d-q frame. Additionally, the air gap permeance functions are developed to simplify the analysis of the air gap magnetic density and the calculation of the parameters, which may make the design flow more efficient. Finally, a prototype is designed and simulated by the FEM, and analytical analyses are carried out to verify and evaluate the HTR-ASD's performance. The comparison between the FEM and the analytical analyses are developed, and the results show great agreement in relation to accuracy. In addition, the results of the operating characteristics indicate that this machine is very suitable for use as an adjustable speed drive.

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