

Article

Design and Performance Analysis of Windings Considering High Frequency Loss and Connection Mode of a Starter Generator

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Abstract: The starter generator is the key component of the aircraft's starter generation system. A high power density, efficiency, and reliability are essential for an aircraft's starter generator. The configuration of the windings is closely related to the performance of the starter generator. In this paper, the winding performance analysis and design are studied. Considering the skin effect, circulation effect, and proximity effect, a calculation model of winding loss under high-frequency operation is established. The motor performance under different winding connections is compared. Through a comprehensive comparison of starting performance, generation loss, and process performance differences, the optimum configuration of windings is identified. The performance of the starter generator including winding resistance, current, and no-load loss was tested on the prototype platform to verify the rationality and correctness of the analysis and design methods.

Keywords: starter generator; motor winding; winding analysis; winding design



Citation: Ren, X.; Chen, Z.; Du, R.; Feng, M. Design and Performance Analysis of Windings Considering High Frequency Loss and Connection Mode of a Starter Generator. *Energies* **2024**, *17*, 5124. <https://doi.org/10.3390/en17205124>

Academic Editor: Chunhua Liu

Received: 10 September 2024

Revised: 12 October 2024

Accepted: 13 October 2024

Published: 15 October 2024



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1. Introduction

The aircraft engine is started by hydraulic and gas turbines [1]. However, the starter becomes redundant after the engine starts, resulting in wasted space on the plane [2]. With advancements in science and technology, there is an increasing reliance on aircraft electricity, leading to a reduction in available space for other components [3]. The development of starter generation technology utilizes the generator within the power generation system as an electric motor to initiate engine start-up [4]. This eliminates the need for a separate starting device for the aero-engine, ultimately saving space and reducing system weight and cost [5,6].

The starter generator is an essential component in an aviation starter generation system [7]. Brushed DC starter generators are commonly utilized in small aircraft and unmanned aerial vehicles [8]. The asynchronous starting generator is favored for its simple system structure and is widely utilized in modern aircraft [9]. However, it requires external reactive excitation power when functioning as a generator, leading to a reduced overall efficiency [10]. Therefore, traditional induction motors and brush DC motors face challenges such as high weight and low efficiency, making it difficult to meet the requirements of a lightweight system [11]. The permanent magnet (PM) synchronous motor presents substantial advantages in aviation starting power generation systems, attributed to its superior power density, efficiency, minimal losses, and compact dimensions [12]. This holds paramount significance for the miniaturization and lightweight optimization of the system [13]. The windings and rotors are critical components closely linked to the motor's performance [14]. Substantial winding loss not only constrains the enhancement of permanent magnet motor efficiency [15], but also results in an excessive temperature rise, leading to potential high-temperature demagnetization of the permanent magnet [16] and impacting the safe and stable operation of the motor [17]. Two winding losses including eddy

and circulating current losses have been studied. The results show that thermal analysis considering winding loss is vital during the primary motor design process [18]. In order to reduce the loss of AC from the winding, a new winding scheme that combines flat wire and Litz wire is presented. In this winding configuration, not only is the higher slot filling rate retained, but the AC loss is also effectively reduced [19]. Improving the performance of permanent magnet motors through advanced winding design has emerged as a focal point in contemporary research on permanent magnet motor design. In the aviation industry, the combination of fractional-slot centralized winding and the permanent magnet built-in structure effectively reduces the mutual inductance of windings and enhances the fault tolerance of permanent magnet motors [20]. The connection mode of the winding is different, which leads to a difference between the phase current and phase voltage when the motor is running, and the working conditions are not the same [21]. A delta winding-connected brushless DC motor is designed based on the nonlinear finite element method, and the cause of torque ripple in the triangle-connected brushless DC motor is studied in [22]. The advantages of the combined star–delta winding, in comparison to the traditional star or delta winding configurations, was presented in [23]. Many studies do not consider high-frequency winding losses, which is no problem for low-speed motors and motors with sufficient cooling space [24]. However, for the starting generator of a space-saving aircraft, if the high-speed motor winding is not fully considered in the design, the motor winding loss will reach a high level, which will affect the efficiency and temperature rise of the motor. In addition, due to its own working environment and tasks, the starter generator needs to work as an engine for a short time and as a generator for a long time. Therefore, its winding design should not only pay attention to the speed and stability of start-up, but also pay attention to the loss in the power generation mode. Most of the existing literature only focuses on one aspect, which is not comprehensive enough for the winding of the starting generator. So, based on the results of previous work including numerical results and other valuable studies, research on how to provide more comprehensive and accurate winding performance analyses is very necessary.

In order to improve the motor system performance, this paper focuses on the accurate calculation of winding loss and research on the connection mode. It lays a foundation for the winding design of a high-performance starter generator. Firstly, the working principle and motor structure of the starter generator are introduced. Second, the factors affecting the winding loss at high frequency are analyzed. On this basis, a precise calculation model of winding loss is derived. Thirdly, the performance of the motor is simulated and compared with the winding in different connection modes. The most suitable connection mode is given. Finally, an experiment is carried out on the prototype platform. The experimental results prove the rationality of the design.

2. Working Principle and Structure

A starter generator uses the reversible principle to reduce the size of the aviation power system, release a lot of space, and also enhance the stability of the system. Figure 1 illustrates a structural diagram of the high-speed permanent magnet starter generator. In the starting phase, the centrifugal impeller serves as the load of the starting generator. The output torque of the starting generator will drive the centrifugal impeller to reach its starting speed. Once ignition is complete, the engine enters a self-running mode. Subsequently, it switches to a power generation mode, and the centrifugal impeller drives the starting generator to rotate at a high speed in order to produce three-phase alternating current (AC). This alternating current is then converted into direct current (DC) through a rectifier circuit to provide stable electricity for the aviation equipment.

As shown in Figure 1, the starter generator adopts an eight-pole and nine-slot structure. The starting speed and torque are 7150 rpm and 0.6 N·m, respectively. The speed range in the generation mode is from 45 krpm to 60 krpm. The rated output power is 2 kW. The main structural parameters of the generator are listed in Table 1.

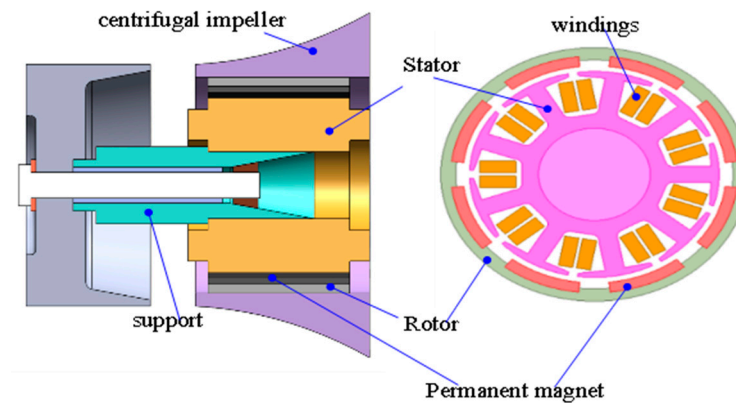


Figure 1. Structure of the starter generator.

Table 1. Design variables of motor optimization.

Name	Value	Name	Value
Poles and slots	8P9S	Pitch	1
Outer diameter of stator (mm)	30.7	Conductors per slot	10
Inner diameter of stator (mm)	13.8	Polar arc coefficient	0.72
Inner diameter of PM (mm)	32.5	Core length (mm)	57
Outer diameter of PM (mm)	35.5	Sleeve material	4Cr13
Number of parallel branches	1	PM material	N35UH
Outer diameter of protective sleeve (mm)	38	Silicon steel sheet	10JNEX900

3. Winding Loss Considering High Frequency

As for high-frequency conditions, the factors influencing winding losses mainly include skin effect, circulation effect, proximity effect, and permanent magnet rotor rotation [25]. The resistance parameters are defined as follows to analyze the winding losses:

$$k_{ad} = R_{ac} / R_{dc} \quad (1)$$

where the coefficient k_{ad} represents the amplification factor of the AC resistance in the winding due to high-frequency effects; R_{ac} represents the AC resistance of the conductor; and R_{dc} represents the DC resistance of the conductor.

3.1. Winding Loss Caused by Skin Effect

When an alternating current is applied to the wire, the loss density inside the conductor differs from that on the surface; specifically, the loss density on the surface of the conductor is higher. The penetration depth serves as an indicator of skin effect severity. The skin depth can be calculated as follows:

$$\delta = 1 / \sqrt{\pi f \mu \sigma} \quad (2)$$

where δ is the penetration depth, f is the alternating current frequency in the conductor, μ is the magnetic permeability of the conductor material, and σ is the electrical conductivity of the conductor material.

Under this situation, the ratio of the AC resistance to the DC resistance of a circular conductor under alternating current can be expressed as

$$k_{ad1} = 1 + \frac{1}{48} \left(\frac{r_{cir}}{\delta} \right)^4 \quad (3)$$

where r_{cir} is the radius of the circular conductor.

3.2. Winding Loss Caused by Proximity Effect

The proximity effect in a conductor is determined by the dimensions of the conductor and the amplitude and frequency of the magnetic field in which it is positioned. The proximity loss in a conductor per unit length is analytically calculated as follows:

$$P_e = \left(\pi d^4 \omega^2 B_n^2 \right) / (128 \rho_c) \quad (4)$$

where d is the diameter of the conductor, ρ_c denotes the resistivity of the conductor, B_n is the amplitude of the magnetic field, and ω refers to the frequency of the magnetic field.

3.3. Winding Loss Caused by Circulated Current Effect

In high-speed motor winding, the circulation effect will lead to additional losses. Given the predetermined stator slot type, the inductance of the conduct is dependent upon the depth of its placement within the slot, irrespective of its tangential position. The amplitude of the leakage magnetic field at a specific depth within the slot remains constant. A greater depth results in a higher wire inductance, while a closer proximity to the slot leads to a lower inductance.

In order to quantify the increase in winding loss caused by the circulation effect, the resistance coefficient can be calculated as at a specific frequency and temperature:

$$k_{ad2} = n \times \left(\sum_{i=1}^n |I_i|^2 \right) / \left(\left| \sum_{i=1}^n I_i \right|^2 \right) \quad (5)$$

where $I_i (1 \leq i \leq n)$ stands for the current in each individual strand, with n representing the total number of parallel winding strands in a parallel branch.

3.4. Winding Loss Caused by PM Rotor Rotation

In certain motor structures, the large stator slot opening can result in the generation of a magnetic field of specific amplitude by the rotor's permanent magnet within the stator slot, leading to additional winding losses. This phenomenon is particularly prevalent in low-speed and low-frequency motors with a power of one megawatt or higher. However, the lower-kilowatt power of the high-speed permanent magnet motor and the general use of semi-closed slots result in a minimal magnetic field amplitude being generated by the rotor's permanent magnets within the stator slot area. Therefore, the additional loss caused by rotor movement is not taken into account in this paper due to the motor's power being 2 KW.

Based on the above analysis, we can calculate the winding loss considering the high-frequency effect as

$$P_{pha} = (k_{ad1} + k_{ad2} - 1) I^2 R_{dc} + P_e \quad (6)$$

where I represents phase current.

4. Winding Connection Mode and Parameter Analysis

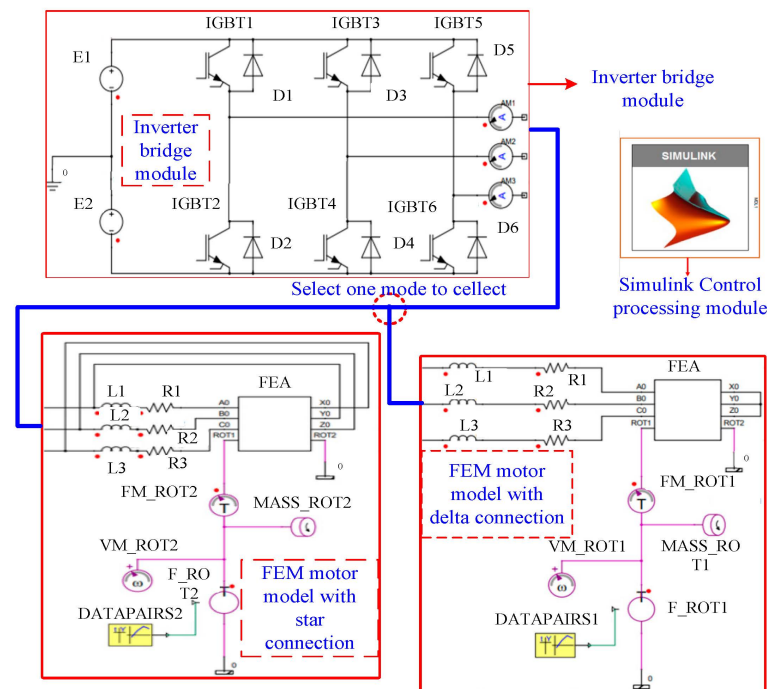
The stator windings of the motor are typically connected in delta or star configurations. In terms of motor design, they exhibit equivalent electrical and magnetic loads. Therefore, for the same motor body geometry size, in order to present the equivalent performance, the key parameters of star- and delta-connected motors are obtained as listed in Table 2.

4.1. Simulation Model

A comprehensive simulation model of a motor with the star or delta connection is established, as shown in Figure 2. The model consists of three modules. The inverter bridge circuit is set up in Simplorer. The electromagnetic performance simulation model of a permanent magnet motor was created in Maxwell. The Simulink module mainly includes PI control and the SVPWM algorithm.

Table 2. Main parameters of winding connection modes.

Parameters	Star Connection	Delta Connection
Number of conductors per slot	6	10
Number of parallel windings	9	9
Wire diameter (mm)	0.53	0.40
Resistance per phase (mΩ)	12.2	36.2
Slot filling rate (%)	74.9	75.3
Air-gap (mm)	0.9	0.9

**Figure 2.** Comprehensive simulation system diagram.

The PI control part includes the speed ring and the current ring of the d-axis and q-axis. It decouples the q-axis current of the motor and realizes the control strategy of the power switch. The SVPWM algorithm control mainly includes the methods of Clarke transform, Park transform, Park inverse transformation, sector calculation, switch-on time calculation, and PWM generation. Based on the calculation of the input three-phase current, the target voltage vector and the rotor position angle in the d–q coordinate system, six chopper output signals are obtained to control the power switch.

4.2. Starting Performance Comparison

The starting speed and torque are designed as 7150 rpm and 0.6 N·m, respectively. The speed curves obtained by simulation are shown in Figure 3. The motors with different winding connections are accelerated from zero at a steady acceleration up to rated speed. It can be seen from Figure 3 that the acceleration times of motors with two winding connection modes are basically the same. The speed of the star-connected motor remains stable at 7246 rpm, while the speed of the delta-connected motor remains stable at 7129 rpm. Compared with the required starting speed of 7150 rpm, the delta-connected motor has a smaller steady-state error. After the speed is stabilized, the linear current waveform of the motor is shown in Figure 4. The root mean square (RMS) values of the linear currents for the star-connected and delta-connected motors are 44.28 A and 44.81 A, respectively, with both motors exhibiting a similar amplitude.

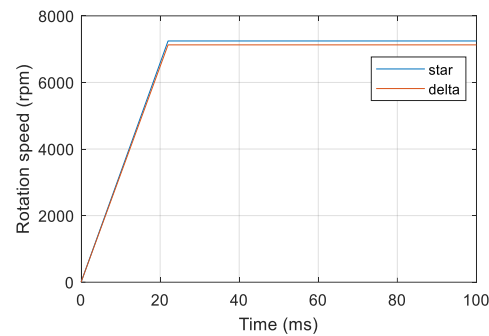


Figure 3. Simulation wave of eddy current loss.

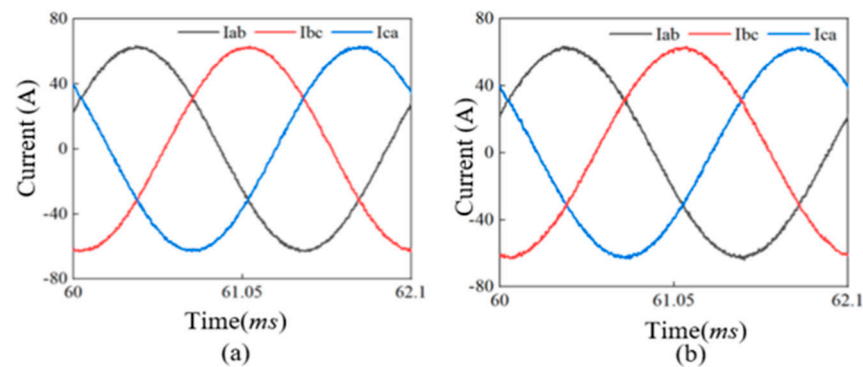


Figure 4. Comparison of starting current curves between (a) star connection and (b) delta connection.

The output torque curves of the star-connected and delta-connected motors are shown in Figure 5. It can be seen from Figure 5 that due to the larger amplitude of the fundamental voltage vector in the delta connection mode, there is an increased stator flux rotation angle within the switching cycle, resulting in amplified torque fluctuation. After conducting the above analysis, it is confirmed that both types of motor winding connections meet the design requirements for a line current RMS of no less than 45 A.

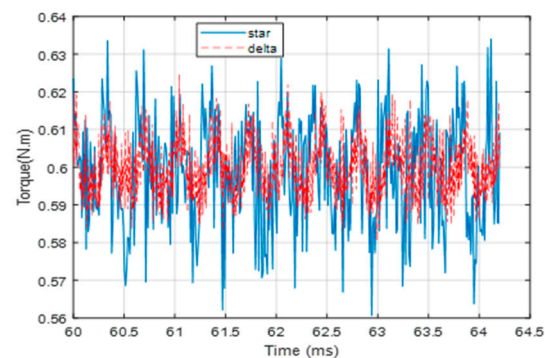


Figure 5. Comparison of output torque waveforms.

4.3. Comparative Loss Analysis of Generator Operating Mode

Due to the influence of the inverter bridge, the phase current of the generator contains significant harmonic components, leading to waveform distortion. Furthermore, high-order harmonics will affect the magnetic field of the motor, resulting in an increase in electromagnetic loss.

4.3.1. Effect on Phase Current Distortion

The degree of phase current distortion varies among different winding connection configurations. In Figure 6, a solid blue line denotes the star-connected phase current waveform, and a red dashed line denotes the delta-connected phase current waveform.

The harmonic spectrum of each current based on Fourier series decomposition is shown in Figure 7. It can be seen from Figure 7 that the third harmonic in the delta-connected phase current is relatively large, while the third harmonic is almost absent in the star-connected phase current. The line voltage of the star-connected generator is the difference between the two-phase voltages, resulting in the cancellation of three harmonic electromotive forces after superposition. As a result, essentially no third harmonic current is generated in the winding. On the other hand, for the delta-connected generator, its line voltage equals its phase voltage, leading to the induction of a third harmonic current in the closed loop due to a third harmonic electromotive force. It can be calculated that the total harmonic distortion of the phase current is 24.2% for the star connection and 25.8% for the delta connection. The presence of the third harmonic component in the phase current results in a slightly higher total waveform distortion rate for the delta connection.

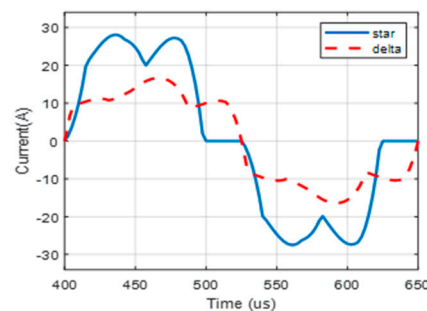


Figure 6. Comparison of phase current waves in star and delta connections.

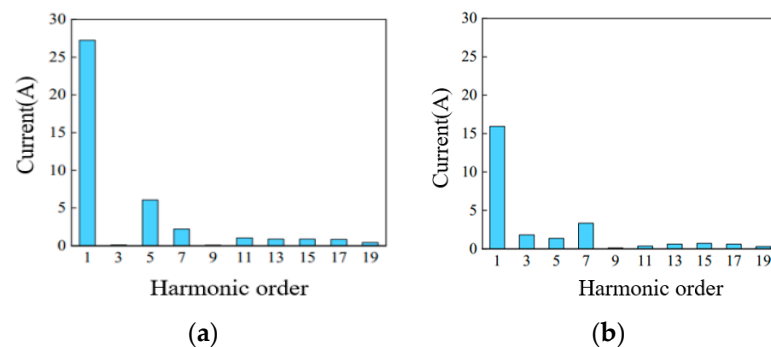


Figure 7. Comparison of phase current harmonic spectra between (a) star connection and (b) delta connection.

4.3.2. Effect on Eddy Current Loss

The presence of current harmonics not only leads to an increase in copper consumption within the winding, but also has an impact on the motor's magnetic field strength, thereby causing an increase in eddy current loss and iron loss. The eddy current distribution of the protective sleeve and permanent magnet under different connection modes is shown in Figure 8. It can be seen from Figure 8 that in the delta connection mode, the eddy current is primarily concentrated at the interface of the protective sleeve and the permanent magnet. The maximum eddy current density on the rotor surface reaches $5.97 \times 10^6 \text{ A/m}^2$. The distribution of the eddy current density on the rotor surface in the star connection mode is similar to that in the delta connection mode, with a slightly lower maximum value.

The electromagnetic loss in generators operating under rated conditions is computed for various connection configurations, as detailed in Table 3. It can be seen that the electromagnetic loss in generators utilizing a delta connection exceeds that of those employing a star connection by 2.8 W.

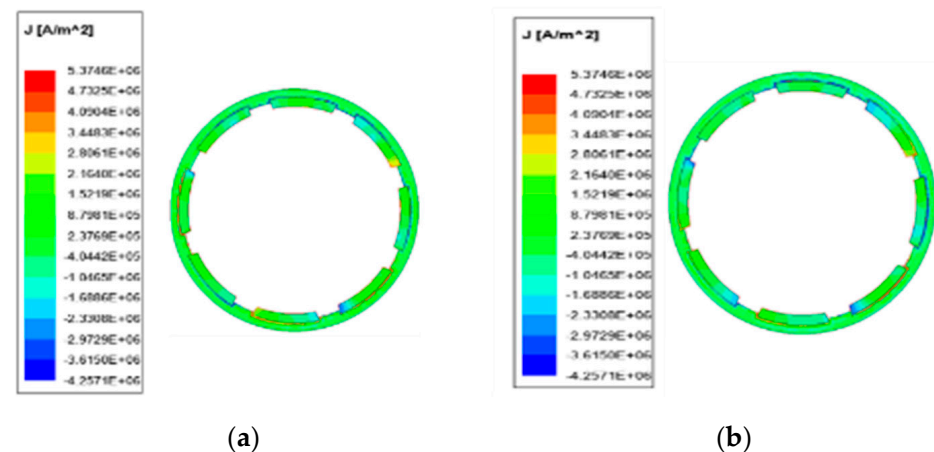


Figure 8. Comparison of eddy current loss between (a) star connection and (b) delta connection.

Table 3. Comparison of losses between generator operating modes.

Loss	Star Connection	Delta Connection
Copper loss (w)	15.4	16.4
Iron loss (w)	43.2	43.8
Eddy current loss (w)	13.5	14.7

Based on the analysis above, the star-connected starting generator offers several advantages. During the starting process, it exhibits a reduced speed and steady-state error and diminished output torque fluctuations, ensuring a more stable initiation. Furthermore, the absence of a third-order current harmonic in the loop results in minimal electromagnetic loss during steady-state generation.

The advantages of delta-connected starter generators include the absence of a common point in the structure, eliminating the need for additional disposal of common points. Additionally, as a starting motor, the basic vector voltage amplitude is larger and the output torque limit is higher. Furthermore, under the same output requirements, a delta connection motor can be designed with more turns, resulting in a smaller wire diameter and lower winding difficulty. In this project, the small size of the generator poses a challenge when using a larger wire diameter for the motor winding installation. Additionally, in order to achieve higher torque output at low voltage, a delta connection is more suitable for the winding.

5. Experiments

The prototype of the starter generator was manufactured and the test platform was set up as shown in Figure 9. As can be seen from Figure 9, the motor drive controller is composed of a main control board, a drive board, and a power device. The main control board mainly includes analog and digital conversion, pulse-width modulation (PWM) signal, controller area network (CAN) communication, and other weak current modules. The driving board is mainly responsible for driving and amplifying the chopper signal, bus voltage and current acquisition, and also includes other strong electric parts. The power device is a high-frequency insulated gate bipolar transistor (IGBT) power module. The starting generator actually works on a flight platform, because there is no complete system test platform yet established with other components such as flywheel energy storage. Therefore, only the starter performance of the starter generator for the engine regime has been tested in this paper, and the power generation performance has not been tested.

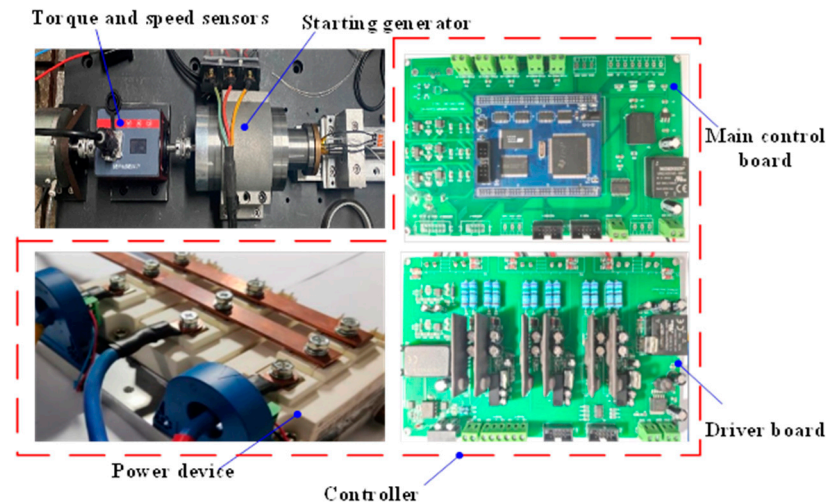


Figure 9. Photo of generator prototype.

5.1. Test of Winding Resistance

The line inductance and line resistance of the starter generator were measured using the LCR tester TH2817A, Changzhou Tonghui Electronic Co., Ltd., Changzhou, China. Table 4 lists the measurement results.

Table 4. Line resistance and inductance measurement values.

Value	A-BC Line	B-AC Line	C-AB Line
Linear resistance (mΩ)	22.96	22.17	23.56
Linear inductance (μH)	19.7	19.31	19.46

Based on the line resistance and line inductance, phase resistance and line inductance can be obtained through the conversion formula. The results of a comparison between the measured values and the simulated values of phase resistance are shown in Table 5. It can be seen that the maximum error between the measured value and the simulated value of the prototype phase resistance is not more than 6.8%. The main reason for the above error is that it is difficult to ensure that the precision of each turn of the coil is completely consistent in the processing process.

Table 5. Line resistance and line inductance measurement values.

Value	A Phase	B Phase	C Phase
Phase resistance (mΩ)	34.04	34.66	35.86
Relative error (%)	6.8%	4.3%	2.8%

5.2. Test of Winding Current

The no-load test involves disengaging the motor output shaft from the torque loader, allowing the motor to overcome friction and wind losses. The oscilloscope records the motor's no-load current at various speeds. Figure 10 shows the experimental waveform of the starting generator current at 15 krpm, and the RMS value of the current is calculated to be 5 A. Compared to the simulated value of 4.6 A, the relative error is 8%. It can be seen from Figure 10 that the winding current waveform has some degree of fluctuation and distortion. The main reason is that the non-inductive algorithm is used to estimate rotor information, which usually introduces high order harmonics and causes current distortion.

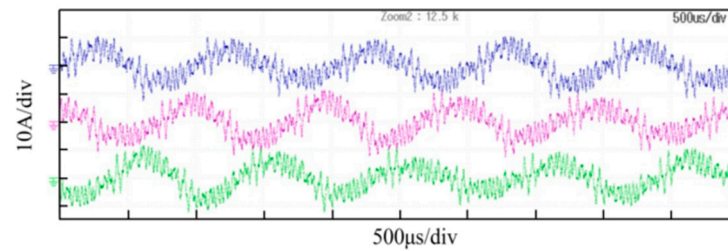


Figure 10. Current waveform with rotating speed of 15 krpm.

5.3. No-Load Loss Test

By measuring the back electromotive force waveform, the back electromotive force coefficient of the starting generator in this project can be established as

$$k_E = 1.47 \text{ V/krpm} \quad (7)$$

The torque coefficient refers to the torque output of the motor in the unit current. After the back electromotive force coefficient has been obtained, the torque coefficient can be calculated by the following equation for a sine wave driven motor:

$$k_T = \frac{9.9593k_E}{1000} \quad (8)$$

where k_T is the torque coefficient and k_E is the back electromotive force coefficient.

Then, the electromagnetic output torque can be calculated as the effective value of the working current times the torque coefficient. The power meter is used to measure the input power of the motor. The working current and input power of the motor at different speeds were measured and are shown in Figure 11. It can be seen that the input power increases in an approximately quadratic function relationship with the increase in speed.

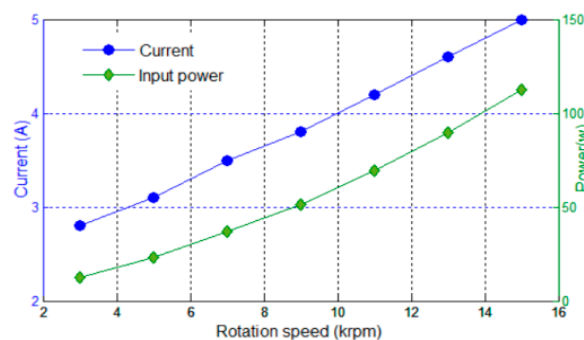


Figure 11. Change in current and power with increasing rotating speed.

The coupling between the motor output shaft and the torque loader is interrupted in the no-load test. At this time, the torque generated by the motor is all used to overcome friction loss and wind damage. Therefore, it can be seen from Figure 11 that at the maximum test speed of 15 krpm, the motor's no-load loss reaches 112.4 W. At the rated speed of 7150 rpm, the no-load loss is 37.7 W.

6. Conclusions

The performance of the winding is closely related to the overall performance of the starter generator. Therefore, winding design is one of the most important parts in the design of a starter generator. Due to the working characteristics of the starter generator itself, it is clear that the winding design should pay attention to both the electric performance and the power generation performance. This paper presents an analysis of winding loss under high frequency considering the impact of the adjacent effect, skin effect, and circulation effect. The precise calculation model for winding loss lays the foundation for the winding

design. The simulation models of the star and delta winding connections are established, respectively. As a starter, the motor performance under the two winding connection modes is compared, including starting speed, starting current, output torque, and phase current waveform. The simulation results indicate that the star connection motor leads to a higher total harmonic distortion rate of phase current compared to the delta connection motor. As a generator, the electromagnetic loss is calculated, and the difference between the electromagnetic loss in the delta connection motor and the star connection is found to be 2.8 W. Through a comprehensive comparison, the delta connection was chosen for the starter generator winding. A platform was constructed based on the prototype. The winding resistance was measured. This showed that the maximum error between the measured value and the simulated value of the prototype phase resistance was not more than 6.8%. At the speed of 15 krpm, the RMS value of the winding test current was about 5 A. Compared to the simulated value, the relative error is 8%. The no-load loss of the motor was tested on the prototype platform. The test results show good motor performance, with a loss of 37.7 W at the starting speed of 7150 rpm and of 112.4 W at the highest speed of 15 krpm in starter operation mode. The good performance of the motor has verified the rationality and correctness of the winding's analysis and design methods.

Author Contributions: Software simulation, formal analysis, experiment, Z.C.; resources, data calculation, experiment, R.D.; programming, experiment, writing—original draft preparation, writing—review and editing, X.R.; supervision, project administration, M.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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