Research Article

Research on the Brushless Excitation System with Linear Current Amplifier Characteristics

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In terms of improving the dynamic response characteristics of brushless AC synchronous generators, the concept of integrated design of AC exciter and rotating rectifier and their electromagnetic characteristics are studied, and the conditions and judgment methods for determining their operating modes are obtained in theoretical design and simulation design, pointing out that when the brushless excitation system operates in or is close to mode III, i.e., the rectifier always has three or four diodes in each operating cycle. The linear current amplifier characteristics can be basically achieved when the brushless excitation system is operated in mode III or is close to mode III, i.e., the rectifier always has three or four diodes alternating in each operating cycle. The impact of the key parameters of the AC exciter at different rotational speeds and temperatures on the characteristics of the linear current amplifier was explored, and an engineering prototype was manufactured. The related test verified the correctness of the concept of integrated electromagnetic design and simulation calculation. This study provides an engineered design method for enhancing the dynamic response properties of the brushless AC synchronous generators.

1. Introduction

The brushless AC synchronous generator, which was developed with the rapid development of power electronics technology, is a new type of motor based on the combination of disciplines such as electrical engineering, electronics, and automation control technology [1]. It uses AC exciter and rotating rectifier as the brushless excitation system to replace the traditional carbon brush and slip ring to provide excitation current for the synchronous generator so that the brushless excitation system no longer has moving contacts, thus the maintenance of carbon brush and slip ring can be avoided. In this way, the reliable, safe, and economical operation of the brushless AC synchronous generator can be achieved.

The brushless AC synchronous generator is usually composed of two parts: the main motor, which can be used as a generator or motor, and a brushless excitation system. It requires an external DC power supply as the excitation power supply for the brushless excitation system, which is called a two-stage brushless AC synchronous generator; some brushless AC synchronous generators also have the third part, namely, the permanent magnet generator, also called pilot exciter, whose main function is to provide excitation power for the brushless excitation system and drive power for the controller. This form can realize the self-excited pressure build-up of the brushless AC synchronous generator without relying on the external power supply, and it is called the three-stage brushless AC synchronous generator. The structure of the two-stage or three-stage brushless AC synchronous generator is shown in Figure 1. The brushless excitation system, composed of the AC exciter and rotating rectifier, is the core part of the synchronous generator to realize brushlessness. The AC exciter is usually designed as a rotating armature electric excitation synchronous generator, and the rotating rectifier is usually designed in the form of three-phase full-bridge uncontrolled diode rectification.
The function of the brushless excitation system composed of an AC exciter and a rotating rectifier is to convert the exciter’s excitation current \( I_{ef} \) to the main motor’s excitation current \( I_F \). The stability of the main motor’s external output voltage is mainly achieved by the adjustment of \( I_{ef} \). Therefore, the goal of designing the brushless excitation system is to meet the excitation needs of the main motor under full working conditions, and at the same time, to reduce the burden of the voltage regulator as much as possible and improve the dynamic response speed of the system. \( I_{ef} \) is required to have a small range of variation under full working conditions; that is, the brushless excitation system should have the linear current amplifier characteristics [2, 3].

Reference [2] proposed and analyzed the design concept of a single-phase AC exciter, studied its operating characteristics in two modes: power generation and start, and concluded that such single-phase AC exciter has linear current amplifier characteristics and approximate constant current source in power generation mode. In the starting mode, the excitation current \( I_{ef} \) of the exciter is almost independent of the speed. Reference [4] proposed a magnetic pole structure with additional short-circuit coils from the perspective of improving the starting output capability of the AC exciter, and pointed out that the short-circuit coil will not affect its performance in the DC excitation power generation mode. However, in reference [2, 4], the focus of the research is laid on the starting performance, and the power generation performance of the AC exciter and the rotating rectifier has not been studied. Reference [3] investigated the basic principles of the linear amplifier of brushless excitation systems at constant speeds and pointed out that the reactance load factor \( \lambda R \) is the dominant factor for determining the operating modal. Reference [5] mainly studied the commutation process of rotating rectifier and analyzed commutation waveform theoretically. Reference [6] explored the operating modal of the brushless excitation system at constant speed and the magnification and linearity of the current amplifier at different temperatures and different loads. However, references [3, 5, 6] have not studied the typical electrical characteristics and the judgment method of each operating modal and how the operating modal affects the current amplifier characteristics under variable speed conditions. In reference [7], the output characteristics and commutation mechanism of the AC exciter as well as rotating rectifier were analyzed, but the judgment method of each operating modal and how the electromagnetic parameters of the AC exciter affect the operating modal were not examined. Reference [8] analyzed and predicted the commutation voltage drop of the diode in the three-phase full-bridge rectifier bridge and used the optimized structure parameters of the AC exciter to achieve smaller commutation voltage drop and higher output capacity, but the operating modal of the rectifier was not discussed in the article.

Although there are a number of researches that have explored the electromagnetic characteristics of AC exciters and rotating rectifiers from different perspectives, they either focus on AC exciters or rotating rectifier. Based on the previous studies, a combination of theoretical analysis and simulation calculation was used in this paper to study the concept and electromagnetic characteristics of the integrated electromagnetic design of the AC exciter and the rotating rectifier, and the conditions and methods for determining its operating modal were summarized. Besides, the influence of the key parameters of the AC exciter at different speeds and temperatures on the linear current amplifier characteristics was analyzed, and it was concluded that when the brushless excitation system works in the modal III or close to this modal, the linear current amplifier characteristics can be basically achieved so that the dynamic response characteristics of the brushless excitation system can be improved.

2. Theoretical Design

The following two indicators are usually used to quantitatively describe the linear current amplifier characteristics of the brushless excitation system:

\[
\begin{align*}
I_F &= K \cdot I_{ef}, \\
\Delta K &= \frac{K_1 - K_2}{K_1} \times 100\%,
\end{align*}
\]

where \( K \) is the current amplification, \( K_1 \) and \( K_2 \) are the current amplification factors under two different operating conditions, respectively, and \( \Delta K \) is the linearity, which is the relative change value of \( K \) under the two load conditions. When \( \Delta K = 0 \), it means that \( K \) is not related to the load state, and the current amplifier is completely linear at this time.

2.1. Theoretical Design of the AC Exciter. The load of the brushless excitation system is the excitation winding of the main motor, which is a large inductive load, and its resistance and inductance are represented by \( R_F \) and \( L_F \), respectively. Then the excitation current \( I_F \) flowing through the excitation winding of the main motor can be approximated as the direct current, and its pulsation component is so small that it can be ignored.
When the brushless AC synchronous generator works at different speeds and temperatures and under different loads, the excitation current \( I_e \) of the main motor may vary within a relatively large range. Therefore, it is required that the output voltage of the AC exciter should vary within a relatively large range, and to achieve linear output characteristics at the same time, the AC exciter can be designed to work in a linear (unsaturated magnetic circuit) state.

After the design of the main motor, since temperature is the only factor that causes the change in the resistance \( R_p \) of the excitation winding of the main motor, when the temperature rise leads to an increase in \( R_p \), in order to keep \( I_e \) output unchanged, the output voltage of the AC exciter needs to be increased. Although the output voltage of the exciter can be increased by increasing \( I_e \), it expands the variation range of \( I_e \), which is inconsistent with the design goal. On the other hand, the electromagnetic parameters of the exciter can be appropriately designed, and the commutation reactance \( X_c \) of the winding of each phase can be increased, thereby changing the operating modal of the brushless excitation system, and achieving the purpose of increasing the output voltage of the exciter while keeping \( I_e \) basically unchanged.

(1) It can be found from references [5, 9] that when the AC exciter is connected to a large inductive load via a three-phase bridge rectifier circuit, the commutation overlap caused by the commutation reactance \( X_c \) of the three-phase armature winding results in short-circuit between the two commutation windings, which reduces the average rectified output voltage. The greater the reactive load factor \( XR \), the larger the commutation angle \( \gamma \), and the greater the loss of commutation voltage drop. The reactive load factor \( XR \) is defined as

\[
XR = \frac{X_c}{R_p} \tag{2}
\]

When the temperature rises, \( R_p \) also increases. The smaller the \( XR \), the smaller the \( \gamma \), and the smaller the loss of commutation voltage drop, which can improve the rectified output voltage.

(2) The potential vector during the stable operation of the exciter is shown in Figure 2. According to reference [7], the internal power factor angle \( \psi \) has the following relationship with the commutation angle \( \gamma \):

\[
\psi \approx \frac{\gamma}{2} \tag{3}
\]

It can be known that the smaller the \( \gamma \), the smaller the \( \psi \), and the smaller the direct-axis current \( I_{df} \), that is, the weaker the \( D \)-axis demagnetizing magnetic field, thus, the air gap magnetic field of the exciter increases when \( I_{ef} \) remains unchanged and the rectified output voltage is improved.

Due to the compensation effect of the above two factors, when \( R_p \) increases with the temperature, the corresponding output voltage of the exciter also increases, which is the theoretical basis for the exciter to realize the characteristics of the linear current amplifier.

![Potential vector during the stable operation of the exciter.](image1)

![Simulated model of the three-phase full-bridge diode uncontrolled rectifier circuit.](image2)

2.2. Theoretical Design of the Rotating Rectifier. In order to deeply analyze the operating characteristics of the three-phase bridge uncontrolled diode rectifier circuit, theoretical analysis was combined with simulation calculation in this paper. The simulated circuit is shown in Figure 3. According to the difference in the time interval of commutation current conversion, the external characteristics expressing the rectified voltage and rectified current can be divided into three operating modals. Modal I: the commutation angle \( \gamma < \pi/3 \), the rectifier always has two or three diode elements working alternately in each operating period; Modal II: the commutation angle \( \gamma = \pi/3 \), the rectifier always has three diode elements working at any time in each operating period; Modal III: commutation angle \( \pi/3 < \gamma \leq 2\pi/3 \), the rectifier always has three or four diode elements working alternately in each operating period. The electrical characteristics of each operating modal are displayed in Table 1, and the voltage source with a certain internal impedance was used to express the external characteristics of the three-phase full-bridge rectifier. \( \alpha' \) in the table is the delay angle.

\[
U_d = U_0 - I_d \times R_{eq},
\]

\[
U_0 = \frac{3\sqrt{2}}{\pi} E,
\]

where \( U_d \) is the output DC voltage of the rectifier, \( U_0 \) is the no-load output DC voltage of the rectifier, \( R_{eq} \) is the equivalent output impedance of the rectifier, and \( E \) is the
effective value of the three-phase line voltage. The rectifier circuit can be divided into two states, conduction and commutation according to the number of rectifier components that are simultaneously conducting. The commutation state includes two-phase commutation (two-phase components that are simultaneously conducting). The commutation according to the number of rectifier components can be divided into two states, conduction and commutation (two-phase short-circuit). The equivalent circuit is shown in Figure 4.

From Figure 4(c), it can be seen that the rectifier voltage is 0 because there are four rectifier elements conducting at the same time, resulting in a short-circuit state on the AC side and DC side. This condition can be used as a basis for judging that the rectifier is working in the IIIrd mode, and the reactive load factor increases. When the reactive load factor $XR$ increases to a certain extent, the equivalent output impedance $R_\text{eq}$ increases significantly. At this time, the change of load impedance has a relatively small impact on the output DC current, and it can be approximated as a current source. When the rotation speed and load resistance change (temperature change), the current amplification $K$ is basically constant; that is, it has linear amplifier characteristics. Therefore, the three-phase full-bridge diode uncontrolled rectifier circuit should be designed with the operating modal III.

| Working modes | Commutation angle | Delay angle | Electrical characteristics | External characteristics | Condition | $R_{\text{eq}}$ |
|---------------|-----------------|------------|---------------------------|------------------------|-----------|--------------|
| I             | $\gamma < \pi/3$ | $\alpha' = 0$ | Conduction and commutation | $U_d = 3\sqrt{2}/\pi E - 3x_{c}/\pi I_d$ | $XR \leq \pi/9$ | $3X_c/\pi$ |
| II            | $\gamma = \pi/3$ | $0 < \alpha'/\pi < 3/2$ | Commutation (two-phase short-circuit) | $2\pi^2/27 \times U_d^2/E^2 + 2I_d^2x_c'/E^2 = 1$ | $\pi/9 < XR \leq \pi/3$ | $3X_c/\pi - 9X_c/\pi$ |
| III           | $\pi/3 < \gamma \leq 2\pi/3$ | $\alpha = \pi/3$ | Commutation (three-phase short-circuit) | $U_d = \sqrt{3} \cdot 3\sqrt{2}/\pi E - 3 \cdot 3x_{c}/\pi I_d$ | $\pi/3 < XR$ | $9X_c/\pi$ |

**Table 1**: Three operating modals.

![Figure 4](image-url)

**Figure 4**: Equivalent circuit: (a) two-phase conduction equivalent circuit, (b) two-phase commutation equivalent circuit, and (c) three-phase commutation equivalent circuit.

It can be seen from Tables 1 and 2 and Figure 5 that when $I_F$ changes, $R_{\text{eq}}$ is related to the commutation reactance $X_c$ and the operating modal of the rectifier and increases as the operating modal of the rectifier increases. When the reactive load factor $XR$ increases to a certain extent, the equivalent output impedance $R_{\text{eq}}$ increases significantly. At this time, the change of load impedance has a relatively small impact on the output DC current, and it can be approximated as a current source. When the rotation speed and load resistance change (temperature change), the current amplification $K$ is basically constant; that is, it has linear amplifier characteristics. Therefore, the three-phase full-bridge diode uncontrolled rectifier circuit should be designed with the operating modal III.

### 3. Electromagnetic Design of the Brushless Excitation System

#### 3.1. Integrated Electromagnetic Design Implementation and Operating Mode Determination

The above theoretical analysis and simulation calculation show that the brushless excitation system composed of the AC exciter and rotating rectifier should have the characteristics of linear current amplifier; that is, $I_{F}$ can meet the variation of $I_F$ within a small range of variation under full load conditions so that the dynamic response ability of the brushless AC synchronous generator system can be enhanced. The reactive load factor $XR$ of the brushless excitation system completely determines its operating modal, and further determines its characteristics of linear current amplifier.
The expression of the definition of XR reveals that the factors affecting the characteristics of the linear current amplifier are the resistance $R_F$ of the excitation winding of the main motor and the commutation reactance $X_c$ of the AC exciter. When the electromagnetic parameters of the main motor are constant, the temperature is the only determinant of $R_F$; $X_c$ is determined by the electromagnetic parameters of the AC exciter. Reference [3] provides the analytical expression of the commutation reactance of the undamped winding exciter:

$$X_c = X_d + X_q$$

Due to the extreme complexity of the electromagnetic equation of the AC exciter and the equation of the external characteristics of the rectifier, as well as the electromagnetic inter-relationship, they should be considered as a whole in the design process. Finite element simulation software can calculate the electromagnetic model and circuit model simultaneously and can provide sufficiently accurate numerical solution in a short period of time, which can save time and cost and improve design efficiency. Thus, it is favored by a majority of engineering designers.

In this study, the influence of the key parameters of the AC exciter on the characteristics of the linear current amplifier was studied through the finite element simulation calculation. Figure 6 shows a simulation model of the original electromagnetic scheme of the AC exciter, denoted by #0, and its basic parameters are displayed in Table 3. An external circuit model for the integrated simulation calculation of the AC exciter and the rotating rectifier was built according to Figure 3. According to reference [10], the three-phase bridge rectifier circuit has higher energy conversion efficiency.

In order to accurately identify the operating modal of the brushless excitation system, the typical characteristics of operating modals I, II, and III were first analyzed.

Operating modal I: according to the above analysis, there are only conduction and two-phase commutation in this modal. Figure 7 shows the curve of the three-phase armature current waveform, where $\theta$ is the conduction angle and $\gamma$ is the commutation angle. In the conduction phase, no current flows through one phase winding, and DC current $I_F$ passes through the two-phase windings, respectively; in the commutation phase, $I_F$ passes through one phase winding. As shown

| Working modes | External characteristics | Condition |
|---------------|--------------------------|------------|
| I             | $U_d^* = 1 - 1/2I_d^*$   | $0 < I_d^* \leq 1/2$ |
| II            | $4/3U_d^* + I_d^* = 1$   | $1/2 < I_d^* \leq \sqrt{3}/2$ |
| III           | $U_d^* = \sqrt{3} - 3/2I_d^*$ | $I_d^* > \sqrt{3}/2$ |

### Table 2: The external characteristics expressed by per-unit values.

| Table 3: Basic parameters of the original scheme (#0) of AC exciter. |
|-----------------------------|-------------------------|
| **Motor form**              | **Rotating armature**   |
| Slot-pole combination       | 10p48s                  |
| Speed (rpm)                 | 8000–16000              |
| Temperature (°C)            | -40–180                 |
| Load resistance (Ω)         | 0.153–0.325             |
| Load inductance (mH)        | 25                      |
| Outer diameter of the stator (mm) | 155                  |
| Inner diameter of the stator (mm) | 107.7               |
| Pole body height (mm)       | 14                      |
| Pole body width (mm)        | 12                      |
| Pole shoe width (mm)        | 25                      |
| Pole shoe height (mm)       | 2                       |
| Field winding wire gauge    | 1 – φ0.8/80             |
| Air gap length (mm)         | 0.5                     |
| Outer diameter of the rotor (mm) | 106.7               |
| Inner diameter of the rotor (mm) | 80                   |
| Armature winding wire gauge | 10 – φ0.56/2            |
| Parallel branches           | 1                       |

![Figure 6: Finite element electromagnetic simulation model of AC exciter.](image-url)

![Figure 5: External characteristic curve (expressed by per-unit value).](image-url)
in Figure 4(b), $I_F$ passes through the two-phase windings participating in the commutation.

Operating modal II: in this modal, only two-phase commutation exists, and there is no conduction. Figure 8 shows the curve of the three-phase armature current waveform, where $\gamma = 60^\circ$. At any time, $I_F$ passes through one of the phase windings, and $I_F$ flows through two-phase windings participating in the commutation.

Operating modal III: in this modal, there is only commutation, and two-phase commutation (two-phase short-circuit) and three-phase commutation (three-phase short-circuit) alternately appear [11]. Figure 9 shows the curve of the three-phase armature current waveform, where $\xi$ angle is the electrical angle corresponding to the time interval of two-phase commutation, $\zeta$ angle is the electrical angle corresponding to the time interval of three-phase commutation, and the commutation angle is $60^\circ < \gamma < 120^\circ$. It can be seen from Figure 4(c) that when the AC side of the rectifier is three-phase short-circuited, the DC side will also be short-circuited. Considering the voltage drop of the diode, the DC voltage $U_d$ will be negative within the interval of $\zeta$ angle. As shown in Figure 10, the negative value of $U_d$ in a certain interval can be used as the basis for judging whether the rectifier is working in modal III.

3.2. Influence of the Main Electromagnetic Parameters on the Characteristics of Current Linear Amplifiers. The inductance parameter of the armature winding of the AC exciter is proportional to the square of the number of series turns per phase, and it is sensitive to the influence of the commutation reactance $XR$. In this paper, the impact of the number of turns of the armature winding on the linear current amplifier characteristics was first studied. A total of three electromagnetic schemes were simulated for calculation: 0#, 1#, and 2#. The 0# scheme is the original electromagnetic scheme, and the number of serial turns of winding per phase is 32. Based on the 0# scheme, the 1# scheme sets empty slots to form a three-phase symmetrical winding with 20 series turns of winding per phase. The 2# scheme sets the number of turns per coil of the 0# scheme to 1 to constitute a three-phase symmetrical winding with 16 series turns of winding per phase. The remaining electromagnetic structure parameters of the three schemes are the same.

Figure 11 shows the curve of the DC output current $I_F$ of the rectifier changing with the excitation current $I_{ef}$ of the
exciter under the working condition where the speed is 16000 rpm and temperature is −40°C in the 0# scheme. Under this working condition, the brushless excitation system works in modal III. It can be seen from the figure that $I_f$ and $I_{ef}$ are approximately linear.

Tables 4–6 provide the operating modal and the parameters of linear current amplifier characteristics of the three electromagnetic schemes. $n$ represents the rotating speed of the generator, $T$ is the operating temperature, and the subscripts min and max represent the minimum and maximum value of the corresponding parameters, respectively. $\Delta K_n@T_{\text{min}}$ means the relative change value of the current amplifier magnification factor $K$ when the brushless excitation system changes from the minimum speed to the maximum speed at the lowest temperature, that is, linearity. Other parameters have similar meaning. The following conclusions can be drawn from the previous theoretical analysis and simulation calculation.

(1) Under the same working condition, the more the number of series turns of winding per phase, the greater the Table 5 commutation reactance $X_c$, the larger the reactive load factor $X_R$, the greater the commutation angle $\gamma$, and the more the improvement of the operating modal of rectifier;

(2) At the same speed in each electromagnetic scheme, the higher the $T$, the larger the $R_p$, the smaller the $X_R$, the smaller the $\gamma$, and the more the operating modal of the rectifier can be reduced. The $K$ decreases with the increase of $R_F$;

(3) At the same temperature in each electromagnetic scheme, the higher the $n$, the higher the electrical frequency of the generator, the larger the $X_c$, the greater the $X_R$, the larger the $\gamma$, and the more the operating modal of the rectifier can be improved. The $K$ increases with the increase of $n$;

Table 4: Operating modal.

| Electromagnetic schemes | $n_{\text{min}}$ | $n_{\text{max}}$ | $n_{\text{min}}$ | $n_{\text{max}}$ |
|-------------------------|----------------|----------------|----------------|----------------|
| 0#                      | III            | III            | III            | III            |
| 1#                      | II             | II             | II             | II             |
| 2#                      | I              | II             | II             | III            |

Table 5: Linear current amplifier magnification.

| Electromagnetic schemes | $n_{\text{max}}$ | $n_{\text{max}}$ | $n_{\text{min}}$ | $n_{\text{min}}$ |
|-------------------------|----------------|----------------|----------------|----------------|
| 0#                      | 11.66          | 12.74          | 12.67          | 13.35          |
| 1#                      | 13.28          | 17.26          | 16.98          | 19.26          |
| 2#                      | 12.19          | 18.95          | 18.32          | 23.13          |

Table 6: Linearity of linear current amplifier.

| Electromagnetic schemes | $\Delta K_n@T_{\text{min}}$ | $\Delta K_n@T_{\text{max}}$ | $\Delta K@n_{\text{min}}$ | $\Delta K@n_{\text{max}}$ |
|-------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 0#                      | 5.37                        | 9.26                        | 8.66                        | 4.79                        |
| 1#                      | 13.43                       | 29.97                       | 27.86                       | 11.59                       |
| 2#                      | 26.26                       | 55.46                       | 50.29                       | 22.06                       |

The air gap length $\delta$ affects the exciter’s magnetic circuit reluctance and armature inductance parameters, thereby influencing the commutation reactance $X_c$. When $R_p$ remains unchanged, the reactive load factor $X_R$ changes, and the operating modal of the rectifier changes accordingly, leading to the changes in the linear current amplifier characteristics. Based on the 0# scheme, the influence of different air gap length $\delta$ on the linear current amplifier characteristics was studied in this paper. To facilitate description, 3#~6# schemes were used. All electromagnetic schemes have basically the same electromagnetic parameters except for the air gap length $\delta$.

Table 7 shows the operating modal of each electromagnetic scheme under different working conditions. Figure 12 shows the curves of Figure 13 current magnification $K$ and linearity $\Delta K$ of each electromagnetic scheme changing with the air gap length $\delta$ at the same speed and temperature. The following conclusions can be obtained: at the same speed and temperature, the smaller the air gap length $\delta$, the smaller the air gap magnetic resistance, the larger the commutation reactance $X_c$, the larger the $X_R$, the greater the $\gamma$, and the more the improvement of rectifier’s operating modal, the larger the $K$, the smaller the $\Delta K$, and the more the linear current amplifier characteristics can be realized.
However, due to the limitation of motor structure and technology, the air gap length should not be further reduced. The axial length \( L \) of the exciter affects the area of the magnetic flux per pole and the total permeability, thereby influencing the commutation reactance \( X_c \). When \( R_F \) remains unchanged, the reactive load factor \( X_R \) changes and the linear current amplifier characteristics of the rectifier will also change. Based on the 0# scheme, this study explored the influence of different axial lengths \( L \) on the characteristics of linear current amplifier. To facilitate description, 7#–10# schemes were used. All electromagnetic schemes have basically the same electromagnetic parameters, except for the axial length \( L \).

Table 8 shows the operating modal of each electromagnetic scheme under different conditions. Figure 14 shows the variation curves of current amplification \( K \) and linearity \( \Delta K \) of each electromagnetic scheme with the axial length \( L \) under the same speed and temperature. The following conclusions can be drawn: at the same speed and temperature, the greater the \( L \), the greater the total permeability, the larger the \( X_c \), the greater the \( X_R \), the larger the \( y \), the greater the improvement of the rectifier’s working mode, the larger the \( K \), and the smaller the \( \Delta K \), so that the linear current amplifier characteristics can be achieved. Besides, with the increase of \( L \), the changes in \( K \) and \( \Delta K \) tend to be smooth, but the volume and weight also increase, resulting in a decrease in the utilization rate of the iron core. Therefore, the length of the iron core cannot be increased blindly under the premise of improving the dynamic response performance.

The load of the brushless excitation system is the excitation winding of the main motor, which is a large inductive load. Its DC current ripple is so small that it can be ignored. The reactive load factor \( X_R \) is inversely proportional to \( R_F \). The value of \( R_F \) is related to the structure of the excitation winding, wire gauge, and operating temperature. Thus, the impact of \( R_F \) on the linear current amplifier characteristics should be fully considered in the design of the main motor. Based on the 2# electromagnetic scheme, this study investigated the influence of \( R_F \) on the linear current amplifier characteristics. Table 9 shows the influence of \( R_F \) on the operating modal of the rectifier when the electromagnetic structure of the exciter is fixed. Figure 16 exhibits how the current amplification changes with \( R_F \). It can be seen that when the electromagnetic structure of the exciter is fixed, \( X_R \) is inversely proportional to \( R_F \). The smaller the \( R_F \), the larger the \( X_R \), the more significant the improvement of the rectifier’s operating modal, and the current amplification factor \( K \) decreases with the increase of \( R_F \).

4. Test Verification

Based on the electromagnetic simulation data, the exciters in 0# (the number of series turns per phase is 32) and 1# (the number of series turns per phase is 20) electromagnetic schemes were produced, which were combined with the same main motor to form a two-pole brushless AC synchronous generator, respectively. In the test, a 200 kW DC motor was used as the prime motor to drive the prototype to rotate, and a 60 V/10A DC power supply was used as the excitation power supply of the AC exciter. The ambient temperature was 15°C, and the generator speed was 12000 rpm. The generator cooling method is oil-cooled, the oil feed pressure is 300 kPa, the oil feed temperature is 70°C, and the oil feed flow rate is 8 L/min. Figure 17 shows the three-phase voltage waveform curve of the main motor with 0.98 A DC current connected to the 0# AC exciter, and its effective value is 115 V. Figure 18 shows the no-load characteristic curve of the generator (the variation curve of phase terminal voltage \( U_0 \) of the main motor and the excitation current \( I_{ef} \) of the AC exciter): in the same exciter electromagnetic scheme, due to the difference in the manufacturing and assembly of the components of the motor, the value of the no-load saturation voltage test is slightly lower than the simulation value, but it can meet the requirement for engineering accuracy. Compared with the 1# scheme since the 0# scheme has more series turns per phase, the commutation reactance \( X_c \) is larger, the commutation angle \( y \) is greater, and the voltage drop loss caused by the commutation overlap is also larger. The average output voltage of the
rotating rectifier is small, the average output current is also small, and the current amplification $K$ is relatively small accordingly. Therefore, under the condition of the same $U_0$, the required $I_{ef}$ is relatively large.

The simulation value of the generator’s no-load characteristic curve is basically consistent with the test value, indicating that the idea and the simulation method for the integrated electromagnetic design of the AC exciter and the rotating rectifier are correct, and the accuracy meets the requirement of engineering design.
5. Conclusion

In order to enhance the dynamic response characteristics of the brushless AC synchronous generator, the excitation current $I_{ef}$ of the brushless excitation system composed of an AC exciter and a rotating rectifier should be able to meet the need of the excitation current $I_F$ of the main motor under full load condition within a small variation range, which means that the brushless excitation system should have the linear current amplifier characteristics. In this paper, the theoretical basis for realizing the linear current amplifier characteristics and the determinant, typical characteristics, and judgment basis of each operating modal of the rectifier were analyzed first. The main contribution is that finite element simulation was adopted to realize the integrated electromagnetic design of the AC exciter and the rotating rectifier, and the influence of the key parameters of the exciter on the linear current amplifier characteristics was explored. When the brushless excitation system works in modal III or close to modal III, the linear current amplifier characteristics can be basically realized. The basis for judging the rectifier operating in mode III is obtained from theory and simulation design and providing a concrete engineering design approach for improving the dynamic response characteristics of brushless AC synchronous generators. Finally, a prototype was made and related test was conducted to verify the correctness of the integrated electromagnetic design and simulation calculation. This study presents an effective design method for improving the dynamic response performance of the AC brushless synchronous generator.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declared that they have no conflicts of interest.

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