Analysis of armature winding open-phase fault in multi-phase annular brushless exciter at nuclear power plant

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Abstract
The multi-phase annular brushless exciter (MPABE) of nuclear power plants has suffered numerous armature winding open-phase faults (AWOPF) in the field operation. In order to achieve reliable protection of the MPABE, its AWOPF is systematically studied through theoretical analysis, simulation calculation and model machine experiments. First, proceeding from the armature current waveform in normal operation and the influence of the AWOPF on it, the armature reaction magnetomotive force (MMF) is analysed deeply. Then, the theoretical analysis about the harmonic electromotive force (EMF) induced by armature reaction MMF on the field winding is presented, obtaining the harmonic characteristics of field current: the even-order field harmonic currents increase obviously under the AWOPF. Finally, correlate experiments and simulations were performed on a customized experimental prototype. The experimental and simulation results are consistent and verify the conclusion of the theoretical analysis, which can serve as a theoretical basis for the monitoring and diagnosis method of the AWOPF in the MPABE.

1 | INTRODUCTION

Nuclear power generation is an important way to obtain low-carbon and clean electric energy, which has broad application prospects. Due to the economic considerations of construction investment, the single-unit capacity of nuclear power plant generating units is continuously increasing. For example, the single-unit capacity of the Taishan Nuclear Power Plant in China, which has just been put into operation in 2019, has reached 1750 MW. Since large-capacity units are equally prone to bring the risk of disturbance to the power system, the safe and stable operation of nuclear power plants has attracted more and more attention.

A reliable excitation system is an essential basis for ensuring the stable operation of the power system. Brushless excitation without carbon brushes and collector ring is the preferred excitation mode for large-capacity nuclear power units. Besides, for the sake of safety, the excitation system is often expected to be capable of short-time redundant operation under certain faults to reduce the significant disturbance caused by sudden machine cut-off. Therefore, a kind of multi-phase annular brushless excitation system is widely used in the large-capacity nuclear power plant generating units (including the Taishan Nuclear Power plant).

The structure of the multi-phase annular brushless exciter (MPABE) system (taking the 11-phase exciter as an example) is
shown in Figure 1. The brushless exciter of this system is a rotating-armature machine, where the field winding is on the stator, while the armature windings are on the rotor and rotate at high speed with the rectifier. In addition, the armature windings are put into an end-to-end annular structure and connect with a multi-phase full-bridge rectifier. Due to the multi-phase structure of the armature windings and the rectifier, the system has low output voltage ripple, high dc power supply quality and a certain fault tolerance [1].

In addition to the electromagnetic force, the armature windings are also subjected to a tremendous centrifugal force due to high-speed rotation. Long-term thermal environment and stress may damage the armature windings and further lead to an armature winding open-phase faults (AWOPF). Under this fault, the excitation system has a redundant operational capability. However, a long-term operation with AWOPF may aggravate the fault, causing serious consequences. The authors have been involved in the analysis of several similar accidents, the most recent of which was the AWOPF of the exciter in a 1250 MW unit at a nuclear power plant in Zhejiang, China, in December 2017. Due to the lack of effective monitoring measures, the early stage AWOPF has not been removed in time. As a result, the armature windings are fractured in many places, which eventually leads to violent shaft vibration of the whole generation and the corresponding protection device tripped. In addition, the burning of armature windings will lead to arcing, resulting in grounding fault and short-circuit fault of the armature windings. Therefore, it is necessary to put forward the reliable monitoring method of the AWOPF of the MPABE.

For the traditional three-phase brushless exciter, experts and scholars have carried out a lot of research on diagnosis methods of different kinds of faults, such as rotating rectifier diode open-circuit fault [2–5], armature windings short-circuit fault [6–9] and field winding short-circuit fault [10,11]. Based on model analysis, signal processing, artificial intelligence and other analysis methods, the fault diagnosis method using electrical signals and physical signals (such as pressure, vibration and temperature) are proposed. Additionally, there are also some references dealing with the fault analysis of the multi-phase brushless exciter, mainly involving the fault analysis of rectifier [12–14], analysis of open-phase operation [15–18], inter-turn short-circuit of stator and rotor [19–21], sudden short-circuit of DC side [22] and other aspects. However, References [3–22] are mainly related to the three-phase brushless exciter and multi-phase star-type brushless exciters. Up to now, there is no relevant research been performed on the AWOPF of multi-phase brushless exciters with annular winding structure.

For the MPABE, References [12,21], respectively, analysed the diode open-circuit fault and exciter stator winding short-circuit fault. They proposed a fault harmonic component detection method based on the detection coil and field winding, which realize online faults detection by harmonic components induced by asymmetric air-gap harmonic magnetomotive force (MMF) on detection coil and. The research mentioned above is with theoretical significance and practical value, which can provide a reference for the analysis of the AWOPF in the MPABE.

Clarifying the fault characteristics is the basis for proposing a monitoring method. As the MPABE is a rotating-armature structure, the electrical quantity on the armature side cannot be directly measured. However, the AWOPF can be detected through the characteristic quantity induced by the fault armature reaction MMF on the stator field winding. Therefore, a comprehensive study on the fault characteristics of stator field current under the AWOPF of the MPABE is made.

This study is arranged as follows. In Section 2, proceeding from the commutation rule of rectifier during normal operation and the influence of the AWOPF on it, the characteristics of armature current during normal operation and the AWOPF are analysed. Then, in Section 3, we analysed the mechanism of the harmonic electromotive force (EMF) induced by armature reaction MMF on the field winding, and obtained the harmonic characteristics of the stator field current before and after the fault. In order to verify the analysis conclusions, the experiments and simulations of an 11-phase annular brushless exciter prototype with AWOPF are carried out in Section 4. Finally, the conclusions are given in Section 6.

2 | ANALYSIS OF ARMATURE CURRENT DURING NORMAL OPERATION AND THE AWOPF

2.1 | Analysis of armature current in normal operation

The field winding of the 11-phase annular brushless exciter is stationary. The armature windings are fractional-slot wave windings, which are evenly distributed on the rotor. The adjacent two-phase armature windings differ by $4\pi/11$ electrical radians in space. The EMF of the adjacent two phases also differ by $4\pi/11$ electrical radians in turn. The connection mode of the armature windings is shown in Appendix A.

According to the connection of armature windings, the EMF vector diagram of the 11-phase armature windings can be drawn, as shown in Figure 2. During normal operation of the exciter, the two diodes corresponding to the maximum line.
The line voltage of the rectifier bridge is the sum of the EMF of several phases of armature windings connected in series. As can be seen in Figure 2, at the moment, the series EMF of armature windings $E_2, E_3, E_4$ is maximum, resulting in diodes $D_3, D_8$ on. After a certain period, the series EMF of $E_{10}, E_{11}, E_1$ will become maximum.

The phaser of the EMF of each phase changes with time and the diodes will alternately conduct in a certain order, as shown in Table 1.

In actual operation, the exciter load is the field winding of a main generator, which has a considerable time constant, so the exciter load current is almost constant, which can be regarded as $I_d$. The current flowing through the armature winding corresponding to the maximum series EMF of the exciter is approximately constant.

Ideally, the inductance of armature windings is ignored; that is, the diode commutation process completed instantaneously. The rectifier diodes are turned on according to the conduction sequence described in Table 1. The corresponding operation-state of the exciter from the time I to time IV is shown in Figure 3.

During normal operation, the conduction diode divides the 11-phase annular windings into two groups. The first group contains three windings with the largest series EMF, while the second group contains the remained eight windings. The two groups supply power to the load in parallel.

Figure 3 takes the phase 2 winding as an example to analyse the changes in armature current under different operating conditions. When the current flows counter-clockwise through the winding in the positive direction, and the load current is $I_d$, it can be concluded that when the first set of conducting windings contains the phase 2 armature winding, the armature current of phase 2 is $\pm (8I_d/11)$; otherwise, it is $\pm (3I_d/11)$.

When the exciter operates in the above sequence, its current waveform is indicated in Figure 4a, and the current value of the armature winding will suddenly change once every commutation.

The presence of the actual armature windings inductance will hinder the current change and smooth the current waveform. Therefore, the actual armature winding current is a periodic waveform consists of three fluctuations per half period, and the waveform reverses every half cycle, as shown in Figure 4b. Since the armature current waveform is an odd function with an electrical period of $2\pi$, its Fourier decomposition will only contain odd harmonics, and for the convenience of theoretical analysis, we can use the square wave in Figure 4c to equivalent armature current waveform, which is also an odd harmonic function contains the most important harmonic frequency of armature current.

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**TABLE 1** Conduction sequence of upper and lower bridge arm diodes

| Time  | I     | II   | III  | IV  |
|-------|-------|------|------|-----|
| EMF   | $E_2 + E_3 + E_4$ | $E_{10} + E_{11} + E_1$ | $E_7 + E_6 + E_0$ | $E_6 + E_5 + E_4$ |
| Diodes| $D_3, D_8$  | $D_3, D_8$  | $D_{13}, D_{13}$ | $D_{13}, D_8$  |
Due to the spatial symmetry of armature windings, the armature current of the exciters during normal operation is a symmetrical current with the phase difference $4\pi/11$ electrical radians in turn. Therefore, the EMF and current of phase $k$ armature winding during normal operation of the 11-phase annular brushless exciter are expressed as follows:

\[
E_k = \sqrt{2}E \sin \left( \omega t - \left( k - 1 \right) \frac{4\pi}{11} \right) \quad k = 1, 2, ..., 11
\]

\[
i_k = \begin{cases} 
I \left( k - 1 \right) \frac{4\pi}{11} \leq \omega t < \pi + \left( k - 1 \right) \frac{4\pi}{11} \\
-I \pi + \left( k - 1 \right) \frac{4\pi}{11} \leq \omega t < 2\pi + \left( k - 1 \right) \frac{4\pi}{11}
\end{cases}
\]

where, $E$ is the effective value of the armature winding EMF and $\omega$ is the angular frequency of the EMF of armature windings.

2.2 | Analysis of armature current under the AWOPF

As shown in Figure 5, the exciter experience an AWOPF of phase 11. Since the field winding is still of symmetrical structure, and the dc component of the stator field current and the EMF of armature windings remain essentially unchanged, the operating rule of the armature winding will not change. It is still conducting when the series EMF of three-phase windings is at its maximum.

However, it is also noted that although the flux linkage generated by the stator field current and [3,4,7,8,13,16,17,20] other winding currents will still induce an EMF in the faulty phase, the armature current of phase 11 will always be zero after the fault due to the lack of leads at both ends of the winding and the inability to form a conducting circuit with the load.

An operation state of the conducting windings including the faulty phase at a certain time is as shown in Figure 6. At this time, the series EMF of corresponding armature windings $E_{11}$, $E_1$ and $E_2$ reaches the maximum. However, the armature current of phase 11 is constant to zero after fault, so the conducting current of remaining windings with the largest combined EMF of phase 11 is zero at the corresponding time. Therefore, as the time indicated in the figure, the armature current of phase 1 and phase 2 becomes zero after the fault.

Because of the three-phase series operation, the current of phase 1 and phase 2 will also become zero when connected in series with phase 11 to supply power to the load. The theoretical waveform and its equivalent waveform in actual operation are shown in Figure 7. The influence of the fault on the armature current of phase 9 and 10 is the same.
The fault current component \( \Delta i \) of one-phase is shown in Figure 8.

The armature current that distorted after the fault can be regarded as the superposition of normal armature current and a fault current component. Thus, the armature current of phases 9, 10, 11, 1 and 2 after the fault can be written as:

\[
\begin{align*}
    i_1' &= i_1 + \Delta i_1 \\
    i_2' &= i_2 + \Delta i_2 \\
    i_9' &= i_9 + \Delta i_9 \\
    i_{10}' &= i_{10} + \Delta i_{10} \\
    i_{11}' &= i_{11} + \Delta i_{11}
\end{align*}
\]  

(2)

Assume that the fault current component of one-phase is as shown in Figure 8.

According to Figure 8, the expression of the fault current component can be written as follows (where \( n = 0, 1, 2, 3, \ldots \)):

\[
\Delta i = \begin{cases} 
    1 & \alpha + 2n\pi \leq \omega t < \pi + 2n\pi \\
    -1 & \pi + \alpha + 2n\pi \leq \omega t < \pi + \beta + 2n\pi \\
    0 & \text{others}
\end{cases}
\]  

(3)

### 3 | HARMONIC CHARACTERISTICS AND MECHANISM ANALYSIS OF STATOR FIELD CURRENT

#### 3.1 | Characteristic analysis of stator field current in normal operation

Fourier decomposition is carried out on the armature square wave current. Since the waveform moves for half a period and the original function are symmetrical about the transverse axis, it means that it satisfies the following relationship:

\[
i(t) = -i(t + \frac{T}{2})
\]  

(4)

Therefore, there are no average and even harmonics in the decomposed Fourier series, only odd harmonic components.

Assume that the \( \mu \)th (\( \mu = 1, 3, 5, \ldots \)) harmonic current in the phase \( k \) is as follows:

\[
i_{k,\mu} = \sqrt{2} I_{k,\mu} \cos \mu \left( \omega t - (k - 1) \frac{4\pi}{P} \right)
\]  

(5)

At any time, the spatial distribution of MMF \( f_{k,\mu} \) generated by the \( \mu \)th harmonic current in the phase \( k \) is still a rectangular wave, but the amplitude of the rectangular wave will alternate sinusoidal with the harmonic current at the angular frequency \( \omega \), and it can be written as:

\[
f_{k,\mu} = \frac{2}{\pi} \frac{N_k}{P} I_{k,\mu} \cos \mu \left( \omega t - (k - 1) \frac{4\pi}{P} \right)
\]  

(6)

where, \( N_k \) is the turns of phase \( k \) and \( P \) is the pole number.

Since the armature windings of the MPABE are designed as fractional-slot and wave structure, the space MMF generated by one-phase armature winding is different under each pair of poles, and its distribution period is \( 2P\pi \), that is, the motor rotes for one cycle, and the MMF under the pole changes for one cycle. Assuming that one-phase winding consists of \( q \) coils, the distribution of MMF induced by it under \( P \) pair of magnetic poles is shown in Figure 9.

Similarly, Fourier is carried out on \( f_{k,\mu} \) for the period \( 2P\pi \), the analysis result contains \( n/P (n = 1, 2, 3, \ldots) \) times harmonic MMF, which will establish corresponding magnetic fields in the air gap. However, due to the spatial symmetry of the field winding, the total EMF induced by the magnetic field is zero when the MMF is fractional and even-order, as can be seen in Figure 10 (e.g., \( P = 2 \)). Therefore, we only consider the effect...
of the magnetic fields generated by fundamental and odd-order harmonic MMF on the field winding.

In order to facilitate theoretical analysis, we established the spatial coordinate system on the stator and the rotor; \( \nu \) is the spatial coordinate of the rotor. Thus, the spatiotemporal expression of the \( \nu \)th (\( \nu = 1, 3, 5, \ldots \)) harmonic MMF generated by the \( \mu \)th harmonic current in phase \( k \) is as follows.

\[
f_{k,\nu,\mu} = F_{\nu-\mu} \cos \left( \omega t - (k - 1) \frac{4\pi}{11} \right) \cos \left( \gamma - (k - 1) \frac{4\pi}{11} \right)
\]

(7)

where, \( F_{\nu-\mu} = \frac{2\sqrt{2}}{\pi} N_{k} k_{dp} I_{k,\mu} \) (\( k_{dp} \) is the armature winding factor of the MPABE), which is the amplitude of harmonic MMF.

Assuming that the coordinate on the stator is \( \alpha \), its positive direction is consistent with the rotating direction of the rotor, when the rotor rotates forward at angular speed \( \omega \) relative to the stator. Then, there is the following relationship according to the relative motion:

\[
\gamma = \alpha + \omega t
\]

(8)

It can be seen that \( f_{k,\nu,\mu} \) are pulse MMF on the spatial coordinates, which can be decomposed into spatial forward and backward MMF by the product to sum formula. Since the armature winding structure and armature current of the exciter are symmetrical, the forward and backward MMF of 11-phase armature winding can be synthesized, respectively, and the resulting expression is as follows:

\[
f_{\nu} = \frac{1}{2} F_{\nu-\mu} \sum_{k=1}^{11} \cos \left( \nu \alpha + (\nu - \mu) \omega t - (\nu - \mu)(k - 1) \frac{4\pi}{11} \right)
\]

\[
+ \frac{1}{2} F_{\nu+\mu} \sum_{k=1}^{11} \cos \left( \nu \alpha + (\nu + \mu) \omega t - (\nu + \mu)(k - 1) \frac{4\pi}{11} \right)
\]

\[
= f_{\nu+} + f_{\nu-}
\]

(9)

As can be seen from Equation (9) that if and only if \( \nu \pm \mu = 11n_{2}(n_{2} \in \mathbb{N}) \), the amplitude of the 11-phase composite MMF \( f_{\nu} \) is not zero. At this time, the \( \nu \)th harmonic MMF generates a spatial magnetic field with a polar number of \( \nu \) in the air gap and a rotational angular velocity \( (\nu \pm \mu)\omega/\nu \) relative to the stator field winding, which will induce the \( (\nu \pm \mu) \)th harmonic MMF in the field winding. Because \( \nu \) and \( \mu \) are both odd numbers, when the 11-phase annular brushless exciter operates normally, the field current mainly contains the dc component and a small amount of 22nd harmonic.

For other exciters with \( m \) phases, when \( m \) is even, the stator field winding mainly contains harmonic currents of the \( m \)-order and its multiples in addition to dc components. When \( m \) is odd, the stator field winding mainly contains harmonic currents of the \( 2m \)-order and its multiples in addition to dc components. Since \( m \) (the number of phases) is generally large, the \( m \)th or \( 2m \)th harmonic current detected in the stator field winding is small.

### 3.2 Characteristic analysis of stator field current under AWOPF

Fourier decomposition of \( \Delta i \) corresponding equation goes here:

\[
\Delta i = \sum_{k=1,3,5} \frac{2I(\sin k\beta - \sin k\alpha)}{\pi k} \cos k\omega t
\]

\[
+ \sum_{k=1,3,5} \frac{2I(\cos k\alpha - \cos k\beta)}{\pi k} \sin k\omega t
\]

(11)

As can be seen from Equation (11), the superimposed fault current contains only odd harmonic currents, which will generate odd harmonic MMF in the air gap. Similarly, it can be seen that the superimposed fault current components of other phases also contain only odd harmonic currents.

It can be assumed that the \( \mu \)th harmonic current in \( \Delta i \) of phase \( k \) is:

\[
\Delta i_{k,\mu} = \sqrt{2} I_{k,\mu} \cos (\mu \omega t + \beta_{k,\mu}) \mu = 1, 3, 5...
\]

(12)

where, \( \beta_{k,\mu} \) is the electrical radian of the \( \mu \)th harmonic current in fault current \( \Delta i \) and \( I_{k,\mu} \) is the effective value of harmonic current.

Consistent with normal operation, each harmonic current will generate MMF in the air gap, which can be decomposed into odd harmonic similarly. Therefore, the \( \nu \)th \( (\nu = 1, 3, 5, \ldots) \) harmonic MMF generated by the \( \mu \)th harmonic current of the fault current component can be expressed in the stator coordinate system as follows:

\[
\Delta f_{k,\nu,\mu} = \Delta F_{\nu-\mu} \cos (\mu \omega t + \beta_{k,\mu}) \cos \left( \alpha + \omega t - (k - 1) \frac{4\pi}{11} \right)
\]

(13)

Since the 11-phase brushless exciter is essentially a salient-pole synchronous motor with symmetrical magnetic poles and uneven air gaps, the air gap reluctance is distributed differently under each pair of poles along the circumferential direction of the stator with a change period of \( 2P_{e} \), so the air gap permeability coefficient \( \lambda \) can be expressed as:
where, $\lambda/2$ is a constant term, $2\ell$ is the harmonic number, and $\lambda_{2\ell}$ is the amplitude of $\lambda$.

Therefore, it can be seen from Equations (13) and (14) that the magnetic field established in the air gap by the $\nu\ell$th $(\nu = 1, 3, 5, \ldots)$ harmonic MMF generated by the $\mu\ell$th $(\mu = 1, 3, 5, \ldots)$ harmonic current in the armature fault current component can be written as:

$$\Delta B_{k,\nu} = \frac{1}{4} F_{\nu - \nu} \sum_{k-1}^{m} \left\{ \cos \left[ (\nu - 2\ell)\alpha \right] + 
\cos \left[ (\nu + 2\ell)\alpha + (\nu - \mu)\omega t - \nu(k - 1)\frac{4\pi}{11} + \beta_{k,\mu} \right] \right\}$$

After the fault, due to the asymmetry of $\Delta i$ in the armature windings, the magnetic field created by the air gap MMF in space still contains odd harmonics at each phase is combined. The $\mu\ell$th harmonic current will establish the $\nu(\pm 2\ell)$th harmonic magnetic field in space, with the pole number being $\nu(\pm 2\ell)$, and the relative stator speed being $(\nu(\pm(\nu(\pm 2\ell)))$ times the synchronous speed, which is $\nu(\pm(\nu(\pm 2\ell)))$ times the synchronous speed, which will induce the $\nu(\pm(\nu(\pm 2\ell)))$th harmonic EMF in the stator field winding. Since $\nu$ and $\mu$ are both odd numbers, it can be seen that the stator field current after the fault mainly contains even harmonic currents in addition to the DC components.

The actual multi-phase brushless exciter has 39, 46 and 51 equal and different phases besides 11. According to the above method, further analysis shows that the stator field current mainly contains DC components during normal operations, while the stator field current under the AWOPF will only have even harmonics, regardless of the phase number.

4 | EXPERIMENTAL AND SIMULATION ANALYSIS UNDER ONE-PHASE AWOPF FAULT IN MULTI-PHASE ANNULAR BRUSHLESS EXCITER SYSTEM

4.1 | Introduction of the experiment and simulation system of the prototype

In order to verify the correctness of theoretical analysis, we have specially designed a prototype with the same structure as the actual 11-phase annular brushless exciter. The difference is that the prototype is designed as a rotating-pole structure so as to conveniently measure the electrical quantities of the armature windings and the diodes. Which means that the armature winding of the prototype is on the stator, while the field winding of the prototype is on the rotor. Obviously, the internal electromagnetic interaction relationship is the same as that of the rotating-armature type. The primary parameters of the exciter prototype are shown in Table 2.

During the experiment, a Yokogawa DL850 oscilloscope is utilized to collect the electrical quantity waveforms of the stator, rotor, rectifier and the load of the exciter under different operating conditions. The experimental device is shown in Figure 11. The 11-phase brushless exciter is driven by a DC motor, and the speed is stabilized at 960 rpm by a governor. At this time, the frequency of armature EMF is 80 Hz. The field winding on the exciter rotor is supplied with stable DC by a DC voltage source, and the AC rectifier of the armature winding is output to the resistance-inductance load through an 11-phase full bridge rectifier.

At the same time, the finite element model is established according to the actual parameters of the exciter prototype, and the simulation calculation matching the experimental
conditions is carried out. Figure 12 shows the finite element simulation model of the exciter prototype, including a visual model and an external circuit. Obviously, from the visual model, corresponding to the experimental prototype, the field winding in the model is on the rotor, while the armature winding is stationary on the stator. It can be seen from the external circuit that the field winding is powered by a DC voltage source, the annular armature winding is connected with a diode rectifier and RL load. The rectifier consists of 22 silicon diodes, and their key parameter is the threshold voltage of starting conduction, which is set to 0.5 V. In general, the voltage of the DC source, the resistance value and the inductance value of the RL load are consistent with the experiment.

4.2 | Comparison of simulation and experiments results of the exciter prototype

In order to ensure the safety of equipment and personnel during the experiment, the field voltage is set at 36V, the field current is kept at about 8.6 A in normal operation, and the load is set at $R_{dc} = 12 \, \Omega$, $L_{dc} = 0.357 \, H$.

In the experiment, the open circuit switch is added between the phase 11 and phase 1. In operation, the open-phase fault is set up by tripping the switch. The oscilloscope records the waveforms of related electrical quantities before and after the fault, while the sampling frequency is 20 kS/s. The waveforms of simulation and experiments are shown in Figures 13 and 14, and the fault occurred at about 1.5450 s.

Comparing Figure 13a with Figure 13b, it is found that the ripple in the simulation waveform of field current and load current is less than that in the experiment waveform, but they are basically consistent. Because simulation is an ideal state, while in the experiment, besides the harmonics introduced by faults, there are also various non-fault factors such as electromagnetic interference, cogging effect and sampling accuracy in normal operation, especially when the sampling frequency of the recorder increases, high-frequency signals will be mixed into the sampled current. Therefore, there will be many ‘clutters’ in the time domain waveform, the change in the experiment waveform of the field current before and after the fault is not obvious, but there is an obvious ripple in the simulation waveform after the fault.

Experiment and simulation waveforms show that the dc component of load current is basically unchanged, that is, the fault has little effect on the load current of the exciter, and the exciter still has a stable output capacity. The waveforms of the armature winding are shown in Figure 14.

By comparison, it can be found that the experiment waveforms and simulation waveforms are completely matched, which verifies the correctness of the experiment and simulation model. It can be seen from Figure 14a that the phase voltage remains unchanged before and after the fault. The armature current of phase 11 is always zero under the fault. The armature current waveforms of phase 1 and phase 10 are distorted, and the current value in two-third period becomes zero. The current

![Figure 13](image-url)
value of phase 2 and phase 9 becomes zero in one-third period. Hence, the experiment waveforms and simulation waveforms are consistent with the theoretical analysis results.

### 4.3 Analysis and discussion

Based on the results of the experiments and simulations, the authors made the following analysis and discussion.

1. **Fault characteristics of field current in the frequency domain.**

   In order to comprehensively analyse the change of field current after fault, we carried out Fourier analysis on the experimental field current before and after the fault. The fundamental frequency is 80 Hz. All harmonic currents (including integer and fractional harmonics) within the seventh harmonic of field current are taken for analysis. The spectrum of the experimental waveform is shown in Figure 15.

   From the spectrum diagram, it can be found that when the multi-phase brushless exciter is in normal operation, the field current contains almost no low-order harmonics except DC component; after the open-phase fault, only the even-order harmonics in the field current increase significantly, which is consistent with the theoretical analysis results.

2. **Characteristics of fault phase electric quantity waveform**

   After analysing the changes of the electrical waveform of each phase after the fault, it can be found that the armature current enters into the steady-state directly without any transient process after the fault. At the same time, it can be seen that the fault will increase the armature current of the non-fault phases, and there is a certain risk in the long-term operation.
5 | EXPERIMENTAL AND SIMULATION ANALYSIS UNDER TWO-PHASE AWOPF FAULT IN MULTI-PHASE ANNULAR BRUSHLESS EXCITER SYSTEM

5.1 | Comparison of simulation and experiments results of the exciter prototype

When two-phase AWOPF occurs, the analysis process of the two-phase AWOPF is similar to that of one-phase AWOPF. The three-phase armature windings connected in series will always flow through the same current. Assuming the open-circuit fault occurs in the phase 10 and phase 11, the waveforms of simulation and experiments of the MPABE after two-phase AWOPF are shown in Figures 16 and 17. The fault time is 0.7887s.

As can been seen from Figure 16(a), just like the one-phase AWOPF, the ripple of field current increases obviously, and the harmonic component appears after the fault in simulation. But in the experiment, the ripple of the excitation current after the fault is not obvious. However, the exciter still has a very stable DC output, which means that it has a tremendous operating redundancy.

The waveforms of the armature winding is shown in Figure 16. Obviously, the experiment and simulation waveforms agree well with each other no matter in the normal operation or under the fault.

Similarly, through the waveforms shown in Figure 17, we can clearly noticed that the phase voltage remains unchanged before and after the fault. The armature current of the phase 11 and phase 10 is always zero under the fault. At the meantime, the current waveform of adjacent armature appears intermittent in different degrees, which is also consistent with the one-phase fault.

When the other two different phases open circuit, the waveform characteristics are basically similar. In order to save the paper space, it is not listed here one by one.

5.2 | Analysis and discussion

Based on the results of the experiments and simulations, the authors made the following analysis and discussion.

(1) Fault characteristics of field current in the frequency domain.

**FIGURE 16** Experimental and simulation waveforms of load and field current. (a) Field current. (b) Load current
Fourier analysis is applied to the field current for one period in the normal operation and two-phase AWOPF of the MPABE, respectively. The fundamental frequency is 80 Hz. All harmonic currents (including integer and fractional harmonics) within the seventh harmonic of the field current are taken for analysis. Finally, the spectrum information of field current is obtained, as shown in Figure 18.

As can be seen from Figure 18, when the MPABE is in normal operation, the field current basically does not contain the low-order harmonic current except the dc component. After the two-phase AWOPF, the even-order harmonic currents in the field current increase significantly, which is consistent with the characteristics of the one-phase AWOPF.

(2) The open-phase fault of non-adjacent two-phase armature windings

The mechanism of non-adjacent two-phase AWOPF is similar to that of one-phase AWOPF. The armature current of the non-fault phase will have regular distortion related to the faulty phase, which can also be analysed by the fault component method. The fault components of armature current also have symmetry, so only even-order harmonic currents can be induced in the stator field winding.
The fault simulation of non-adjacent two-phase faults is carried out, in which the phase 9 and phase 11 armature windings of the exciter are disconnected for operation. Fourier analysis is performed on the data of one period of field current after the fault, and the fundamental frequency is 80 Hz. After the open-phase fault of non-adjacent two-phase armature windings, the field current of the exciter stator also contains only even-order harmonics. This point is also demonstrated for the faults of other different phases, which will not be listed one by one. The characteristic analysis of field current under different faults is illustrated in Figure 19.

Compared with one-phase AWOPF, when the non-adjacent and adjacent tow-phase AWOPF occurs, the effective value of total harmonic current in field current is increased, which means that distinguish one-phase AWOPF from two-phase AWOPF by using the total effective value of harmonics is an effective method.

6 | CONCLUSION

The AWOPF of the MPABE are analysed from three levels of theoretical analysis, prototype experiment and simulation. Through the comparison and verification of the three levels, the general conclusion of the fault characteristics of the field current is obtained, which are as follows:

(1) When the MPABE is in normal operation, the exciter field current contains only a minuscule amount of harmonic components related to the phase number, in addition to dc components.

(2) In the event of AWOPF of the MPABE, in addition to the dc component, the field current mainly contains even-order harmonic currents.

The research in this study can serve as a basis for the detection of the AWOPF of the MPABE. The next step is to discuss the influence of the AWOPF on exciters in detail, and then the criterion, setting and outlet mode of fault protection method will be studied. From the analysis, it can be seen that the effective value of stator field harmonic current caused by the fault is small, so it is necessary to further study the influence factors of characteristic quantity and fault detection algorithm.

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APPENDIX

| TABLE A1 | Connection table of the armature windings |
|----------|------------------------------------------|
| Phase    | Connection sequence                      |
| 1        | 1-16-31-46-61-76-14                      |
| 2        | 29-44-59-74-12-27-42                     |
| ...      | ...                                      |
| 11       | 50-65-3-18-33-48-63                     |