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Open-circuit Fault Diagnosis and Fault-tolerant Control Strategy for Parallel Three-phase Rectifiers

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***Abstract*-- In this paper, an open-circuit fault diagnosis and fault-tolerant control strategy for parallel three-phase rectifier are proposed. The different characteristics of three-phase rectifier under normal condition, single switch open-circuit fault and double switch open-circuit fault are analyzed in depth. A fault diagnosis method based on the harmonic content of the switching bridge arm is studied, and a method based on neural network is designed to analyze the harmonic content of the bridge arm to locate the fault switch of three-phase rectifier. The power quality characteristics of three-phase traction substation are analyzed, and a comprehensive compensation control strategy is proposed, which combines the positive sequence and negative sequence double closed-loop control with predictive current control. The correctness and effectiveness of the fault diagnosis method and integrated compensation control method are verified by simulation and experiment.**

***Index Terms*—Flexible traction converter, Three-phase rectifier, Open-circuit fault diagnosis, fault-tolerant control strategy.**

I. INTRODUCTION

Traction power supply system is one of the four core systems of railway. The existing traction power supply system is equipped with neutral sections, which is difficult to realize energy interconnection. In order to solve the problems existing in the traditional traction power supply system, the advanced traction power supply system with flexible traction converter as the core equipment of active power transmission has attracted wide attention in the industry [1, 2]. The flexible traction converter is composed of a variety of active and passive devices. Compared with the traditional traction transformer, the reliability of the flexible traction converter is low because of its complex structure and many devices. However, the flexible traction converter has a higher degree of modularization, convenient data acquisition, controllability and adjustability, and its fault diagnosis and self-healing capabilities are strong [3]. Therefore, it is of great significance to carry out the research on its fault diagnosis and self-healing strategies.

The existing traction power supply system and several new traction power supply systems are analyzed and compared in this paper. Considering the various parameters of the existing switching devices, a flexible traction converter structure based on three-phase to single-phase three-level cascaded and parallel converter is studied, which is shown in Fig.1. In the flexible traction converter, the parallel three-phase rectifier plays an important role in the safe operation of three-phase power grid [4- 6].

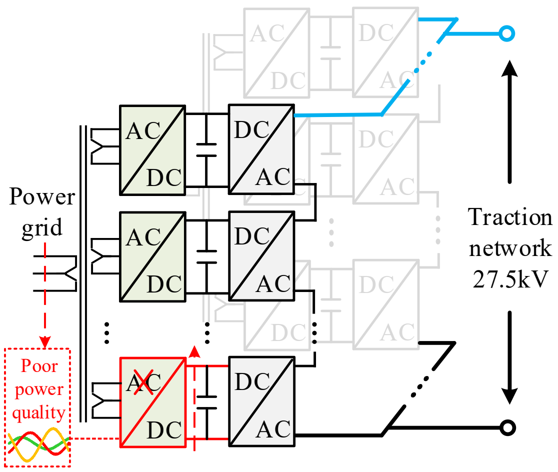

Fig. 1: Flexible traction converter structure

Fig.1 is the schematic diagram of the influence of the parallel three-phase rectifier after IGBT open-circuit failure. The power quality of the three-phase power grid would be affected due to the open switch failure. Meanwhile, the value of the DC-link voltage would also be unstable. Therefore, it is very important to realize the diagnosis and fault-tolerant control of the open-circuit fault of the parallel rectifier for the stable operation of the system [7, 8].

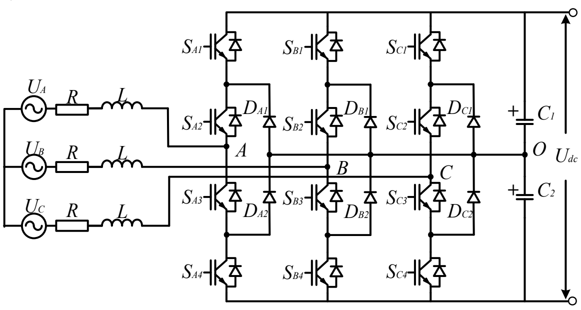

Fig. 2: Topologic of three phase NPC rectifier

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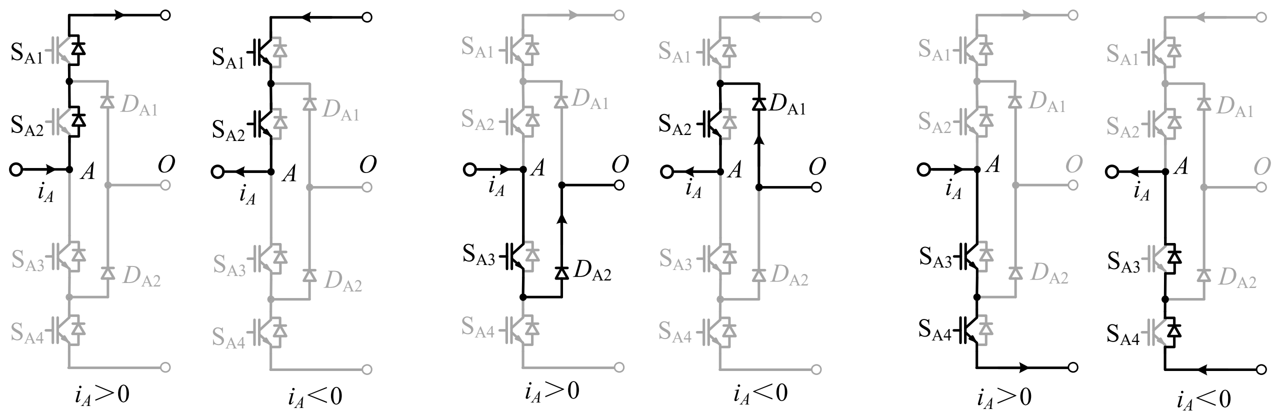

(a) S_A= [1 1 0 0] (b) S_A= [0 1 1 0] (c) S_A= [0 0 1 1]

Fig. 3: Current path of the bridge arm A

TABLE I
TEN FAILURE TYPES FOR NPC RECTIFIERS

Fault Switch	Switch state of arm A		U_{AO}	
	Normal	Fault	$i_A>0$	$i_A<0$
S_{A1}	1 1 0 0	0 1 0 0	$1/2U_{dc}$	0
S_{A4}	0 0 1 1	0 0 1 0	0	$-1/2U_{dc}$
$S_{A1}+S_{A4}$	1 1 0 0	0 1 0 0	$1/2U_{dc}$	0
	0 0 1 1	0 0 1 0	0	$-1/2U_{dc}$
S_{A2}	1 1 0 0	1 0 0 0	$1/2U_{dc}$	$-1/2U_{dc}$
	0 1 1 0	0 0 1 0	$-1/2U_{dc}$	$-1/2U_{dc}$
$S_{A1}+S_{A2}$	1 1 0 0	0 0 0 0	$1/2U_{dc}$	$-1/2U_{dc}$
	0 1 1 0	0 0 1 0	0	$-1/2U_{dc}$
$S_{A2}+S_{A4}$	1 1 0 0	1 0 0 0	$1/2U_{dc}$	$-1/2U_{dc}$
	0 1 1 0	0 0 1 0	0	$-1/2U_{dc}$
	0 0 1 1	0 0 1 0	0	$-1/2U_{dc}$
S_{A3}	0 1 1 0	0 1 0 0	$1/2U_{dc}$	0_c
	0 0 1 1	0 0 0 1	$1/2U_{dc}$	$-1/2U_{dc}$
$S_{A1}+S_{A3}$	1 1 0 0	0 1 0 0	$1/2U_{dc}$	0
	0 1 1 0	0 1 0 0	$1/2U_{dc}$	0
	0 0 1 1	0 0 0 1	$1/2U_{dc}$	$-1/2U_{dc}$
$S_{A3}+S_{A4}$	0 1 1 0	0 1 0 0	$1/2U_{dc}$	0
	0 0 1 1	0 0 0 0	$1/2U_{dc}$	$1/2U_{dc}$
$S_{A2}+S_{A3}$	1 1 0 0	1 0 0 0	$1/2U_{dc}$	$-1/2U_{dc}$
	0 1 1 0	0 0 0 0	$1/2U_{dc}$	$-1/2U_{dc}$
	0 0 1 1	0 0 0 1	$1/2U_{dc}$	$-1/2U_{dc}$

II. FAULT STATE CHARACTERISTICS

A. Normal conditional

Three phase NPC rectifier is widely used in the industry to improve the pressure level. If open switch tube fault occurs in the three-phase rectifier, the dc side stability of each module will be affected first, and the normal operation of the cascade inverter will be seriously affected. In addition, under normal circumstances, the three-phase rectifier works in the unit power factor state, when the switch tube failure, will affect the power quality of the three-phase power grid side.

For example bridge arm A, the two capacitor voltages are considered equal during analysis in normal condition. In this condition, there are three switching states of bridge A arm, [1 1 0 0], [0 1 1 0], [0 0 1 1].

B. *IGBT Open-circuit Failure Characteristic*

As shown in Table I, there are a total of 10 failure types for NPC rectifiers, taking into account single and double tube failures. This paper analyzes the S_{a2}+S_{a3} fault as an example. Fig.4 is the current path of the bridge arm A when S_{a2}+S_{a3} fault. Specific circulation mode is no longer repeated here.

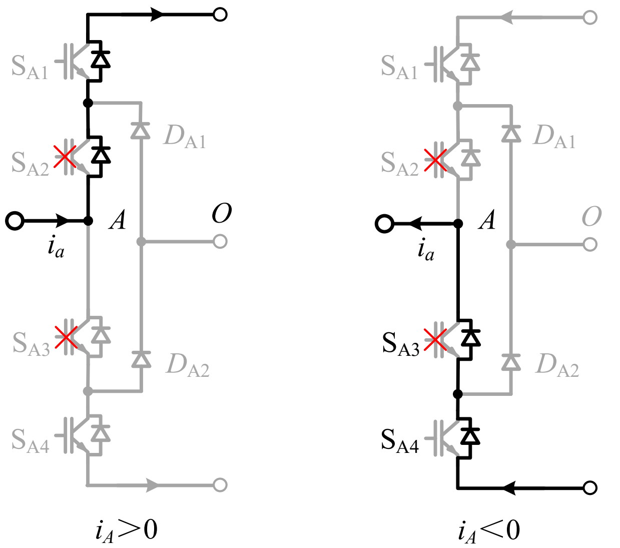

Fig. 4 Current path of the bridge arm A when S_{a2}+S_{a3} Fault

III. Fault Diagnosis And Fault-Tolerant Control Strategy

Because the control system cannot recognize the waveforms of different faults directly, a method is needed to realize the accurate diagnosis of multiple faults. Since the output voltage is a periodic signal when the fault occurs, the output state of the bridge arm voltage varies with different fault types, and the harmonic content must be significantly different. Therefore, the frequency spectrum analysis results of the output voltage waveform of the faulty bridge arm can be used as the characteristic information of fault diagnosis.

According to the bridge arm voltage of different faults, spectrum analysis is made on the voltage of each bridge arm, and spectrum waveform is obtained as shown in Fig. 5.

In formula (1), m represents carrier frequency, n= ±1, ±3... Represents the upper and lower odd-order side frequencies of the harmonics of a carrier. When the system works normally, the output voltage spectrum of the bridge arm only contains odd harmonic items in the integer multiple sideband of carrier frequency. Fig. 5(a) shows the output voltage spectrum of bridge boom A under normal conditions. It can be seen from the figure that the main harmonic components are 17th, 19th, 21st, 23rd harmonics and 40th harmonic sideband.

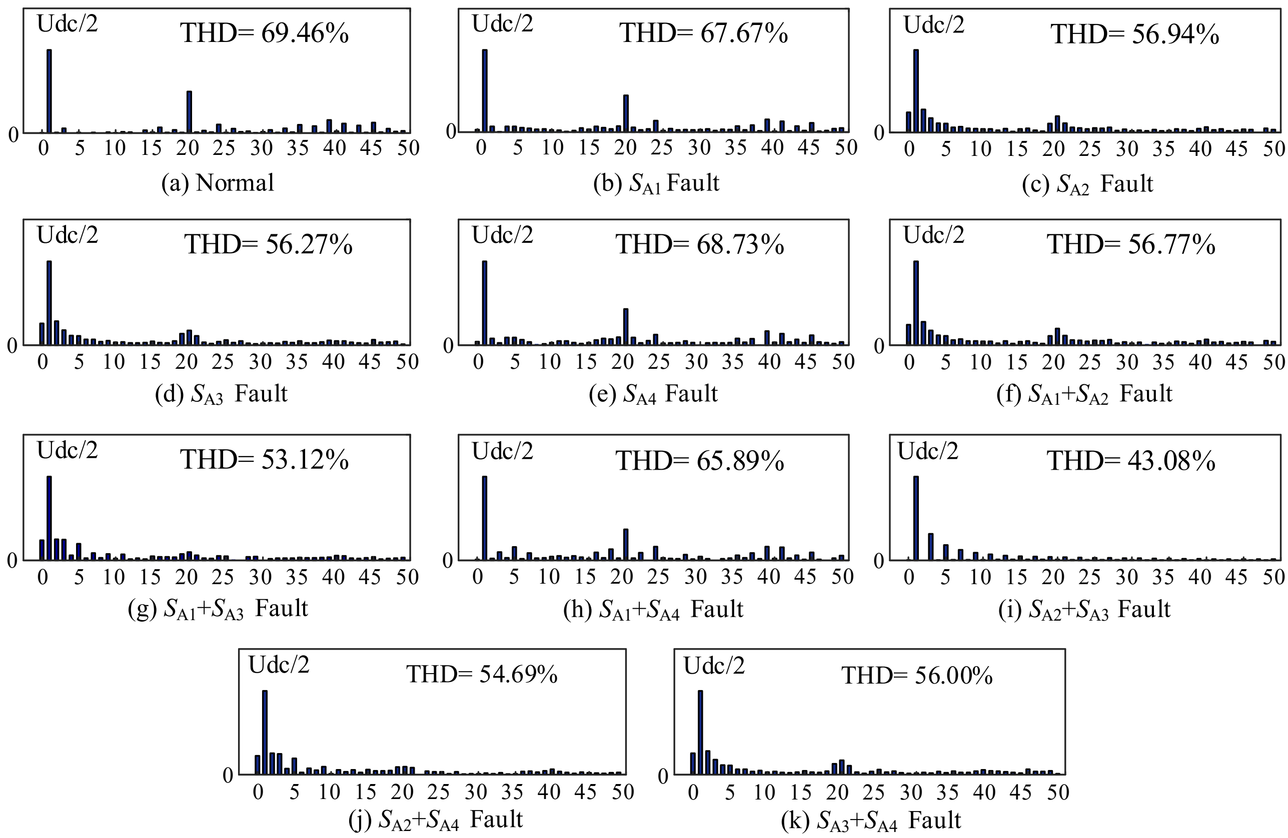

Fig. 5: Frequency spectrum of output voltage of bridge arm A in typical fault mode

$$F_a(\omega_c t,\omega_v t) = F_{PWM1}(\omega_c t,\omega_v t) + F_{PMW2}(\omega_c t,\omega_v t) =$$
$$\frac{M}{2}\cos(\omega_v t) + \mathrm{e}^{\text{-jm}\alpha}(1+\mathrm{e}^{\text{-jm}\pi})\frac{1}{m\pi}\sum_{m=1,2,\cdots}^{\infty}\sum_{n=\pm1,\pm2,\cdots}^{\pm\infty}[J_n(\frac{mM\pi}{2})\cdot\sin(\frac{m+n}{2}\pi)\cos(mF\omega_v t + n\omega_v t + n\frac{\pi}{2})] \quad (1)$$

Because it is difficult to establish a simple corresponding relationship between the output spectrum and various faults, and when the modulation system changes, even if the same fault, the output waveform and its spectrum characteristic parameters will change. As shown in Fig.6, this paper establishes neural network to achieve accurate fault diagnosis.

According to the above analysis, when the three-phase rectifier has an open-circuit fault, the port voltage of the faulty bridge arm will be distorted, which will not only cause voltage instability on the DC side, but also cause current distortion on the network side of the three-phase rectifier. This will cause serious harm to the safe and stable operation of the parallel three-phase rectifiers. Fig. 7 is the control diagram of the proposed comprehensive compensator. It can be seen from the figure that the comprehensive compensation strategy includes dc side capacitor voltage stability control strategy, fundamental current and harmonic current control strategy.

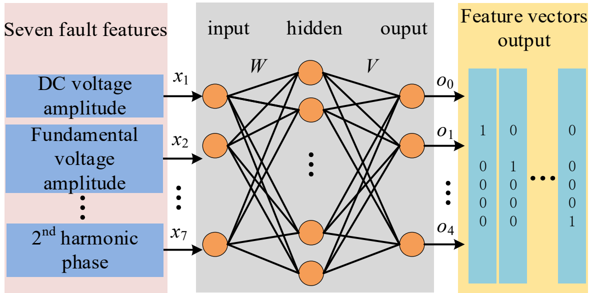

Fig. 6: Frequency spectrum of output voltage of bridge arm A in typical fault mode

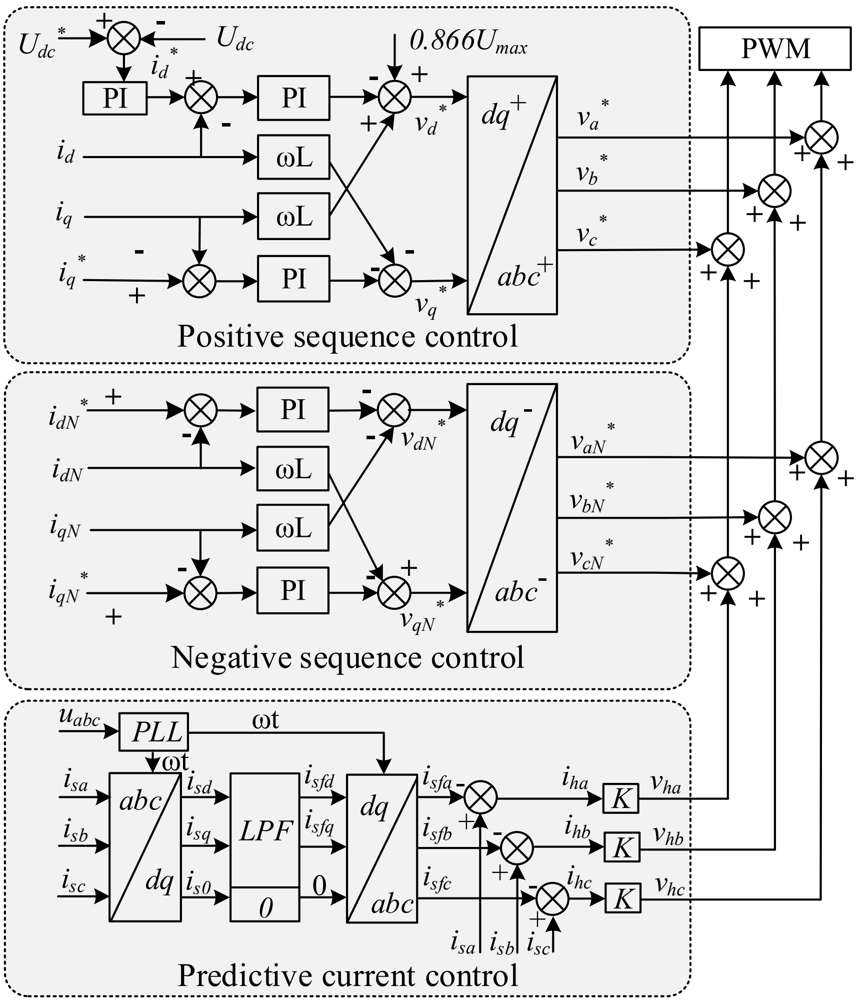

Fig. 7: Integrated compensator fault-tolerant control

IV. Experiment

In order to verify the correctness of the fault diagnosis strategy studied in this chapter. The low power experiment was set up to verify the fault diagnosis. Experimental waveforms are shown in Figure 8-12.

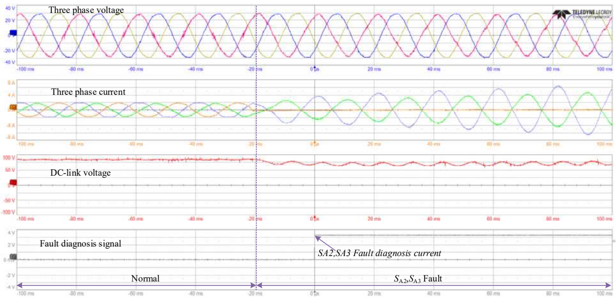

Fig. 8: Fault diagnosis experimental waveform

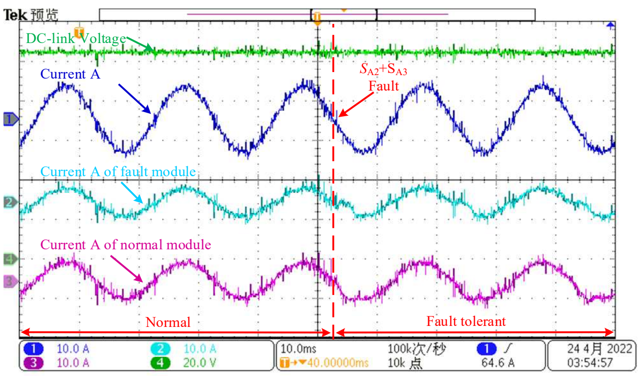

Fig. 9: Current waveform of each parallel rectifiers

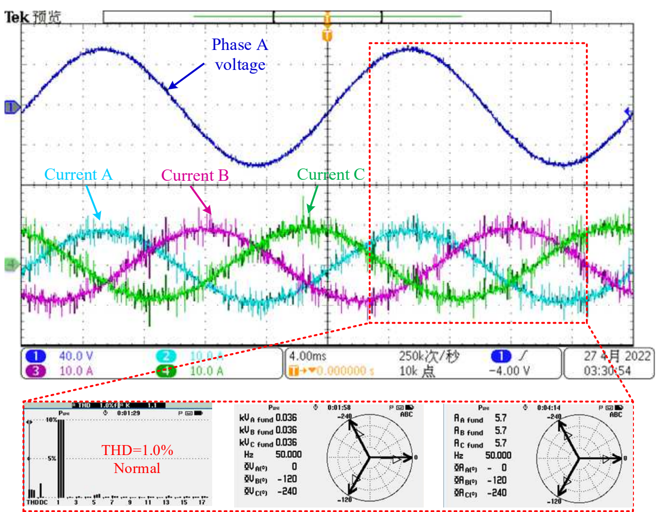

Fig. 10: Three-phase rectifier in normal state

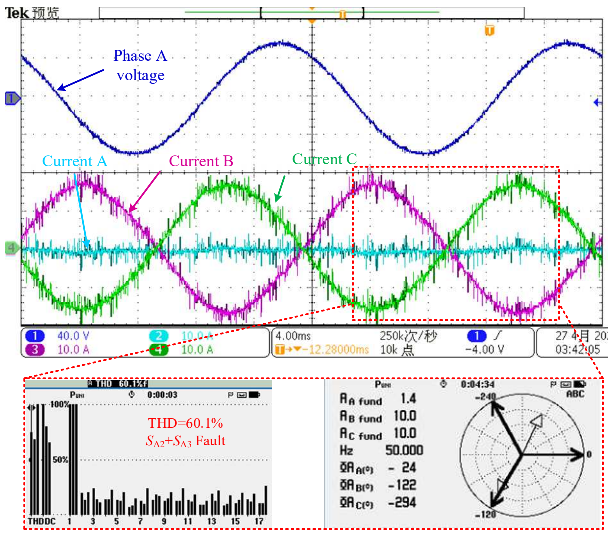

Fig. 11: Three-phase rectifier when S_{A2}+S_{A3} fault

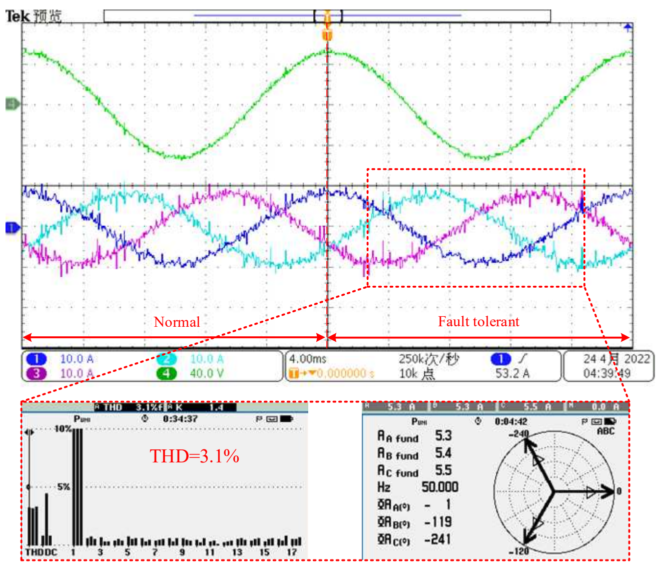

Fig. 12: Power grid waveform after fault tolerance

V. Conclusion

In this paper, A fault diagnosis method and a fault tolerance strategy for open circuit fault of three-phase rectifier switch tube are proposed. 10 kinds of open circuit fault are divided into 4 kinds of fault modes. S_{A2}+S_{A3} open circuit fault has the most serious influence, which will make the three-phase network side current missing phase and produce serious power quality problems. The proposed fault diagnosis strategy can realize the fault location time within 20ms. The integrated compensation self-healing strategy can ensure that the power factor of three-phase network side is higher than 0.99, the unbalance degree of three-phase current is lower than 2.18%, and the total harmonic distortion rate is lower than 3.1%.

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