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Research on Open Circuit Fault Location and Fault Tolerant Control of Inverter Power Transistor

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Abstract: As the key equipment of power conversion, the stability of the inverter directly affects the working state of the equipment. Aiming at the open circuit fault of the power tube, this paper designs a fault diagnosis and fault tolerance scheme of a three-phase bridge inverter based on the current signal. Firstly, the amplitude and phase characteristics of the current vector are used to judge the fault and fault location of the power tube. Then the output fault characteristic signal is converted into a fault-tolerant control signal. The fault leg is switched into a fault-tolerant leg under fault-tolerant control of the inverter bridge. The simulation results show that the diagnosis method proposed in this paper can judge the health and fault status of the inverter with high accuracy and achieve fault tolerant control, improving the stability of the inverter.

1. Introduction

With the development and progress of science, technology, and civilization, a large number of power conversion equipment has been widely used. As an important energy conversion equipment, inverters have gradually become the focus of relevant research [1]. The working stability of the inverter directly affects the overall working state of the equipment. In many complex working environments, the power tube will experience varying degrees of aging or failure, thus leading to various kinds of faults [2]. If the fault occurs, the equipment will be damaged in light cases, and the system will be paralyzed in serious cases [3]. Therefore, timely detection and accurate judgment of inverter faults are the keys to ensuring system safety and maintaining equipment operation. Among the many failures of the inverter, the switching devices are more prone to failure than other components because of their frequent on and off in the inverter circuit and the harsh working conditions. If they fail, they will have a great impact on the equipment. Among the common switching devices, IGBT (Insulated Gate Bipolar Transistor) has the advantages of high current, low driving power, low on-state voltage drops, and fast switching speed, which is widely used in various inverter bridges. The main IGBT faults are open-circuit faults and short-circuit faults. Short-circuit faults are prone to overcurrent and cause greater harm to the system, but mature protection schemes are available [4].

In contrast, open-circuit faults are less likely to trigger the protection circuit. If they are not detected and handled in time, open-circuit faults can easily lead to secondary faults, resulting in more serious consequences [5]. Meanwhile, according to a survey of more than 200 products from 80 companies such as Siemens, ABB, Schneider, etc., the probability of failure of IGBT in power equipment is 34% [6]. IGBT open-circuit faults frequently occur, which are difficult to judge, and affect the equipment badly, so they are highly valued among the major faults.

At present, several scholars have conducted research on inverter power tube open-circuit faults. By improving the current vector instantaneous frequency method, the vector's instantaneous frequency residuals and angular characteristics can be used to locate the faulty phases, and the combination of the average value of the three-phase currents can achieve locating the faulty components [7]. The two-phase output currents ia and ib are derived into elliptical trajectories in a Cartesian coordinate system. The diagnosis of single-tube open-circuit and double-tube open-circuit faults is achieved by observing and identifying the current trajectories [4]. The diagnosis of power tube faults is achieved by training a random vector function connection network with three-phase current fault data and using a data-driven approach instead of fault mechanism model analysis [8]. Using the phase angle characteristics of the current park vector, after partitioning a current cycle, the fault is determined by comparing the change in scan time for each partition, which has strong robustness but increases the computational effort [9]. The method of using the normalized value of the average value of the three-phase stator current and the normalized value of the current product as fault diagnosis variables is proposed to distinguish between single- and double-tube open-circuit faults in inverters, but the method has the problem of slow diagnosis speed [10]. The threshold value is determined using the iterative method, and the 13 fault modes of the neutral-clamped three-level inverter can be identified by combining the values of the threshold and the phase angle [11]. The MLD (Mix Logical Dynamical) model of the current is constructed using the current residuals as the basis for judgment, and the rate of change of the residuals is used to locate the fault [12]. It can be found that some achievements have been made in the research on inverter faults. However, the above-mentioned methods mainly focus on fault diagnosis and ignore the fault tolerance problem after a fault occurs. Two sets of inverter structures were studied, and this system-level structure design improves the safety and reliability of the drive system to some extent but greatly increases the complexity of the system [13]. The fault mode of the three-level ANPC traction inverter is analyzed, and the fault-tolerant control strategy under the open-circuit fault of a single power device is designed based on space vector modulation [14]. Fault tolerance control in case of open-circuit faults is achieved by adding additional power devices, but this method has drawbacks such as high cost and large size [15]. When the fault occurs, the three-phase four-open tube topology is studied, which means the fault phase is connected to the capacitor neutral through the thyristor, and the system works in the three-phase four-switch state. This topology has a low voltage utilization rate and can only cover the single tube fault of the inverter [16]. This paper mainly focuses on the amplitude and phase information of the current vector when the power tube is an open-circuit fault. An inverter state diagnosis and fault location method based on the direct current method is proposed, and a bridge arm redundancy method is put forward to realize fault tolerance. The methods are tested by a fault diagnosis and fault-tolerant control simulation model built in MATLAB/Simulink environment. The experimental results show that this method can accurately judge and locate the switching device's fault and achieve fault-tolerant control.

2. Direct current method working principle

Currently, three methods are commonly applied for IGBT open-circuit fault diagnosis: model judgment method, signal judgment method, and data-driven judgment method [17], of which this paper focuses on the direct current method among the signal-based diagnosis methods. The direct current method can make the diagnosis of all open-circuit faults of single and dual power tubes. Its principle is to use current vector instantaneous frequency characteristics and current vector instantaneous angular characteristics for fault diagnosis [7], which analyzes the fault characteristics of the current signal based on the current vector method. Further, it retrieves the characteristics that distinguish different fault types using information such as park transform and period characteristics. Further derivation on the basis of the current vector method can be obtained from the ideal trajectory of single tube open circuit and double tube open circuit of partial fault type and the corresponding vector phase.

Equation 1 is used to determine the standard deviation of the measured curve from the normal operating curve because the vector phase changes significantly after a fault occurs. Then the standard deviation is used to determine whether a fault has occurred in the segment.

$$\sigma_x = \sqrt{\frac{\sum_{K=1}^{N}(x_k - \mu)}{N}} \qquad (1)$$

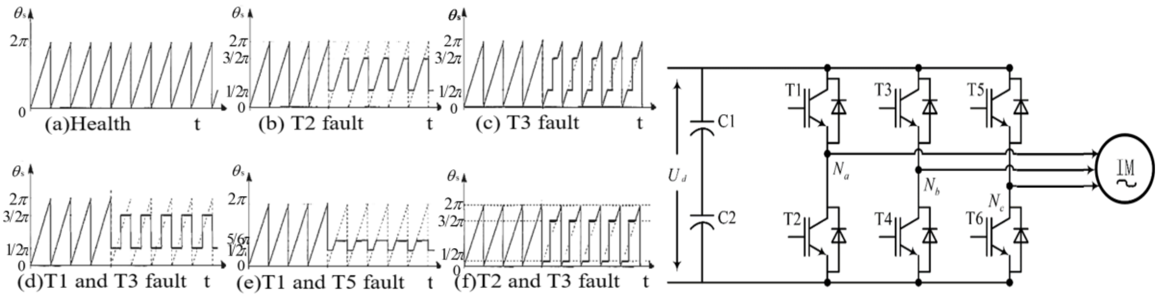
Where, x_k is the current vector sampling data at k moments (k=1, 2, ..., N), μ is the mean value of sample data, and N is the number of current vector data sampling windows. To reduce the computational effort and improve the diagnostic speed, the sampling window length can be set to 1/20 of the current fundamental period [18].

The fault detection threshold is K_d, and the standard deviation of the vector to be measured is σ_p. The fault is judged when $\sigma_p < k_d$. The standard deviation of the vector in normal operation is σ_{ph}. Ideally $k_d = \sigma_{ph}$, but to improve the accuracy of detection, the value k_d should be less than σ_{ph}. To improve the reliability of the fault detection results, while drawing on the results of other scholars' research [18], the equation $k_d = 1/4\sigma_{ph}$ is used as the fault detection threshold.

After determining that a fault has occurred in the power tube, the fault location is determined based on the current vector characteristics. The distance between the vector coordinates and the origin can be found first, and then the direction of the vector motion can be deduced from the distance. The characteristics of the current vector phase can be described by the fault characteristic variables so that the characteristic values of the fault characteristic variables can be further deduced under different faults, as shown in Table 1. θs is the fault characteristic value. It is the phase of the fault electric vector located in the radius but not on the circumference; expressed in the electric vector phase diagram is the corresponding Y value when the function image is parallel to the horizontal coordinate. The electric vector phase diagram of the healthy state and part of the fault is shown in Figure 1 (a). Figure 1(b) shows the topology of the three inverter circuits, where T1-T6 correspond to the six power tube switching devices in the inverter bridge, respectively.

Table 1 Fault characteristic variables for each type of fault

Status	Fault location	$\delta\theta s$
Health	—	—
Open circuit fault	T1	-3π/2、π/2
	T2	-π/2、3π/2
	T3	-π/6、7π/6
	T4	-7π/6、π/6
	T5	-5π/6、11π/6
	T6	-3π/2、5π/6
	T1、T3	-3π/2、7π/6
	T1、T5	-5π/6、π/2
Open circuit fault	T3、T5	-π/6、11π/6
	T2、T4	-π/2、π/6
	T2、T6	-11π/6、3π/2
	T4、T6	-7π/6、5π/6
	T1、T4	-7π/6、π/2
	T1、T6	-3π/2、5π/6
	T2、T3	-π/6、3π/2
	T3、T6	-11π/6、7π/6
	T2、T5	-π/2、11π/6
	T4、T5	-4π/6、π/6



(a) Partial fault type electric vector phase (b) Inverter circuit topology

Figure 1 Phase diagram of the electric vector corresponding to each switching tube fault of the inverter

According to θs , the fault location can be achieved. Let (i=a, b, c; j=1, 2) be the fault localization variables, a, b, and c correspond to the three-phase bridge arms, 1 and 2 correspond to the upper and lower bridge arms, and then we have Equation 2.

$$\begin{cases} \left|\delta\theta_s + \frac{3\pi}{2}\right| < \theta_{th} \,||\, \left|\delta\theta_s - \frac{\pi}{2}\right| < \theta_{th}, \quad P_{a1} = 1 \\ \left|\delta\theta_s - \frac{3\pi}{2}\right| < \theta_{th} \,||\, \left|\delta\theta_s + \frac{\pi}{2}\right| < \theta_{th}, \quad P_{a2} = 1 \\ \left|\delta\theta_s + \frac{\pi}{6}\right| < \theta_{th} \,||\, \left|\delta\theta_s - \frac{7\pi}{6}\right| < \theta_{th}, \quad P_{b1} = 1 \\ \left|\delta\theta_s - \frac{\pi}{6}\right| < \theta_{th} \,||\, \left|\delta\theta_s + \frac{7\pi}{6}\right| < \theta_{th}, \quad P_{b2} = 1 \\ \left|\delta\theta_s + \frac{5\pi}{6}\right| < \theta_{th} \,||\, \left|\delta\theta_s - \frac{11\pi}{6}\right| < \theta_{th}, \quad P_{c1} = 1 \\ \left|\delta\theta_s - \frac{5\pi}{2}\right| < \theta_{th} \,||\, \left|\delta\theta_s + \frac{11\pi}{6}\right| < \theta_{th}, \quad P_{c2} = 1 \\ \text{Other situations}, P_{a1}, P_{a2}, P_{b1}, P_{b2}, P_{c1}, P_{c2} = 0 \end{cases} \quad (2)$$

Where θ_{th} is the phase judgment threshold, considering all kinds of disturbances and measurement errors, θ_{th} should be slightly greater than 0. According to Table 1 and P_{ij} , the fault diagnosis criterion of the direct current method can be deduced.

3. Application of the improved direct current method in fault tolerant control

3.1. IGBT open-circuit fault state diagnosis method based on the direct current method

This article focuses on the detection, location, and fault-tolerant design of the open power tube fault, which is the main fault of the three-phase full-bridge inverter circuit. Combined with Equation 2, the preset correspondence between fault number and fault location in this paper is shown in Table 2.

Table 2 Fault number and location correspondence preset and fault judgment basis

Status	Fault Type	Fault number	Fault Location	Pa1	Pa2	Pb1	Pb2	Pc1	Pc2
Open circuit failure	Single tube open circuit fault	1	T1	1	0	0	0	0	0
		2	T2	0	1	0	0	0	0
		3	T3	0	0	1	0	0	0
		4	T4	0	0	0	1	0	0
		5	T5	0	0	0	0	1	0
		6	T6	0	0	0	0	0	1
	Heterogeneous same side double tube	7	T1、T3	1	0	1	0	0	0
		8	T1、T5	1	0	0	0	1	0
		9	T3、T5	0	0	1	0	1	0

		10	T2、T4	0	1	0	1	0	0
		11	T2、T6	0	1	0	0	0	1
		12	T4、T6	0	0	0	1	0	1
	Heterophase heterolateral double tube	13	T1、T4	1	0	0	1	0	0
		14	T1、T6	1	0	0	0	0	1
		15	T2、T3	0	1	1	0	0	0
		16	T3、T6	0	0	1	0	0	1
		17	T2、T5	0	1	0	0	1	0
		18	T4、T5	0	0	0	1	1	0
	Double tubes in Same phase	19	T1、T2	1	1	0	0	0	0
		20	T3、T4	0	0	1	1	0	0
		21	T5、T6	0	0	0	1	1	0
Health	None	22	None	0	0	0	0	0	0

The detection system first determines the health and fault status of the inverter. The traditional detection method in the direct current method compares the standard deviation of the phase of the fault state and the healthy state, but this method is not reliable in practical application. Figure 2 shows the standard deviation of the current angle phase of fault number 16 in Table 2 compared with the standard deviation in the healthy state, which obviously does not meet the criteria $k_d < 1/4\sigma_{ph}$.

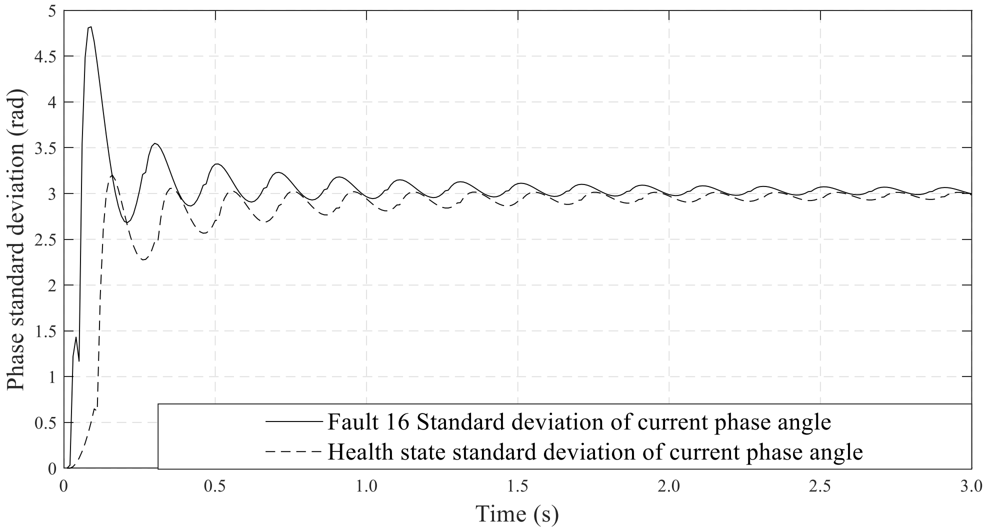


Figure 2 Comparison of the standard deviation of phase in fault sequence number 16 and healthy state

Since the method described in the direct current method is ineffective and complex in practice, this paper improves the direct current method by selecting the current amplitude as the basis for judgment and distinguishes the inverter health from the fault state by detecting whether the current amplitude is over zero. The primary reason is that in a healthy state, it is not possible to descend to 0 because the current amplitude is stable in a fixed range. By contrast, the magnitude of the fault state changes. There is a process of decreasing from radius to 0 and then increasing from 0 to radius, and the magnitude can be 0. Ideally, the image of the magnitude function of all faults can be over zero. The characteristics are obvious. The method described in the article can make accurate judgments on faults without judging the most values and resetting the difference data, which is more concise and more reliable, but still requires multiple judgments to avoid fluctuating effects such as start-up disturbances.

3.2. IGBT open-circuit fault location diagnosis method based on the direct current method

The fault characteristic value θs is the differential value of the current phase before and after the current trajectory flows through the coordinate origin. Ideally, the zero position obtained in the direct current method can be used directly to retrieve the phase value θs at the time points before and after it. However, this method requires too high a current waveform, and such an ideal waveform cannot be obtained in practice. There will be too much error between θs and the theoretical fault characteristic value even if the direct current method is solved in a certain time period before and after the zero position. If the phase judgment threshold is set too large for this case, it will lead to other fault misclassification. In addition, there is also the problem of how to set the length of this period of time. The length of the time period t in this method and phase judgment threshold θ_{th} in the parameters of different devices are to be adjusted accordingly to ensure that its judgment results are relatively reliable. It is difficult to use this method to diagnose the location of the open circuit fault.

Therefore, in this paper, the six possible fault eigenvalues $\theta s'$ near $\pi/6$, $\pi/2$, $5\pi/6$, $7\pi/6$, $3\pi/2$, $11\pi/6$, are retrieved, and the time that the current phase stays in each $\theta s'$ interval is recorded separately. The two $\theta s'$ outputs in which the current phase stays the longest are the finalized fault characteristic values θs. The same fault characteristic values Ia, Ib and Ic are then introduced for different faults to be distinguished.

3.3. Fault-tolerant design for open-circuit faults based on the direct current method

The fault-tolerant design in this paper mainly consists of a fault diagnosis module, a fault-tolerant control module, and a fault-tolerant bridge, as shown in Figure 3. The fault tolerance module is mainly used to determine the power tube health status and its fault location information, mainly through the amplitude and phase characteristics of the current vector, to determine the power tube fault status and fault location. The fault-tolerant control module mainly converts the fault signal of the circuit into a fault-tolerant control signal. The fault-tolerant bridge path adopts a bridge arm redundancy method. The fault-tolerant bridge path is mainly switched according to the fault-tolerant control signal, which mainly controls two fault-tolerant half-bridge arms.

4. Open-circuit tube failure example

Three-phase full-bridge voltage-source inverter is the most widely used, so this paper mainly analyzes the power tube open-circuit fault, and the control signal is SVPWM (Space Vector Pulse Width Modulation) modulation by default. The design and detection in this paper are simulated in MATLAB/Simulink environment.

4.1. IGBT open-circuit status diagnosis

This paper adopts a signal-based approach for the detection of power tube open-circuit faults. It carries out current amplitude detection for the health state and various power tube open-circuit fault types, respectively, to determine the magnitude of the amplitude and the set value to determine whether the amplitude is able to touch zero. The test model for simulation selected typical load conditions for the experiment. Figure 4 (a) indicates the current amplitude in the healthy state, and Figure 4 (b) indicates the current amplitude in the fault 19 state. It can be seen from the figure in a certain load, all the current amplitude of the fault state can be taken to the set value of 0.2A or less, while the healthy state amplitude is generally between 60-75A. Its characteristics are obvious, so it can complete accurate judgment of fault. In order to avoid the impact of fluctuations such as start-up disturbances, the method is more concise in conducting the detection but still requires multiple judgments, but the method does not need to judge the most value and does not need to reset the difference data.

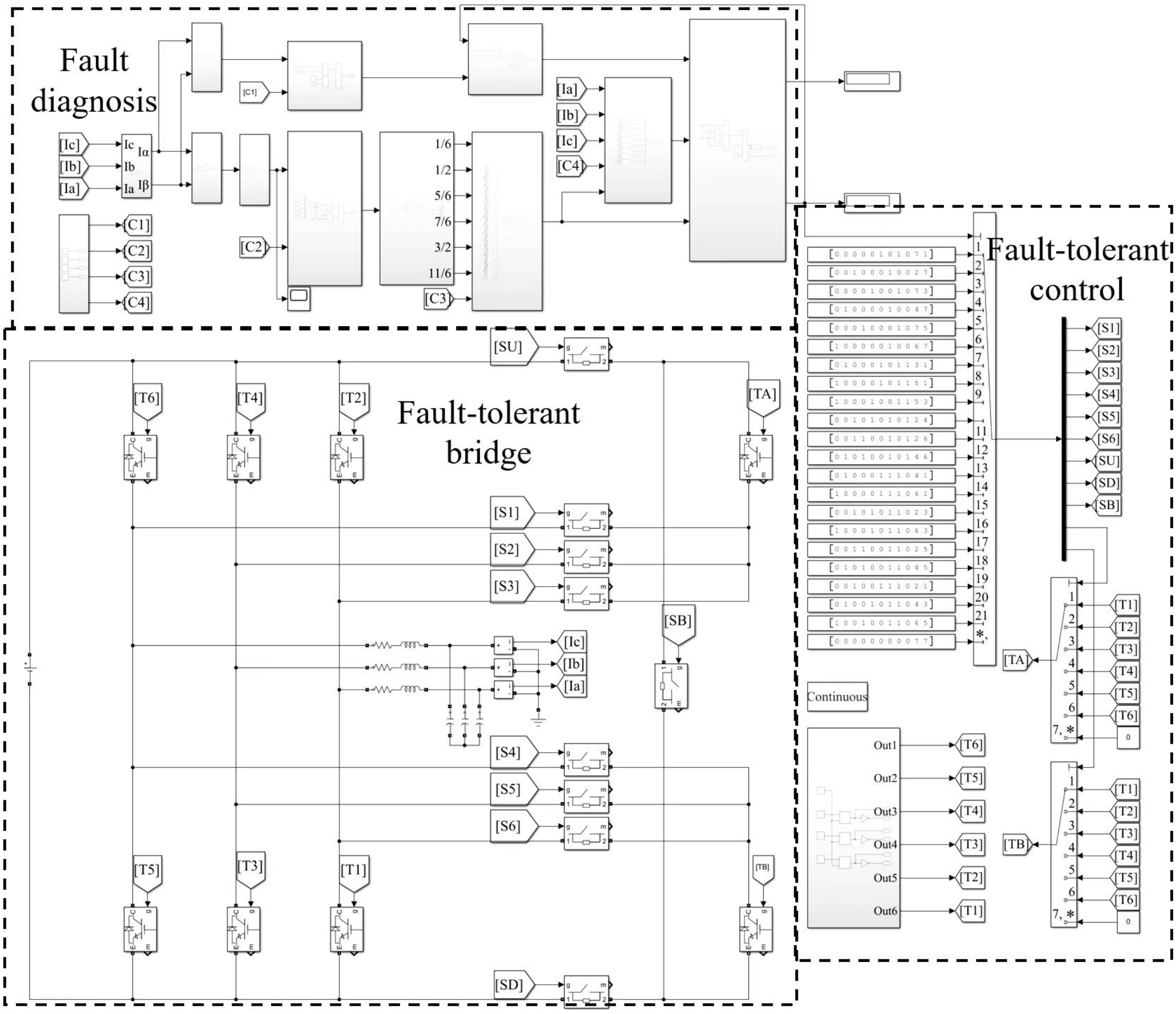
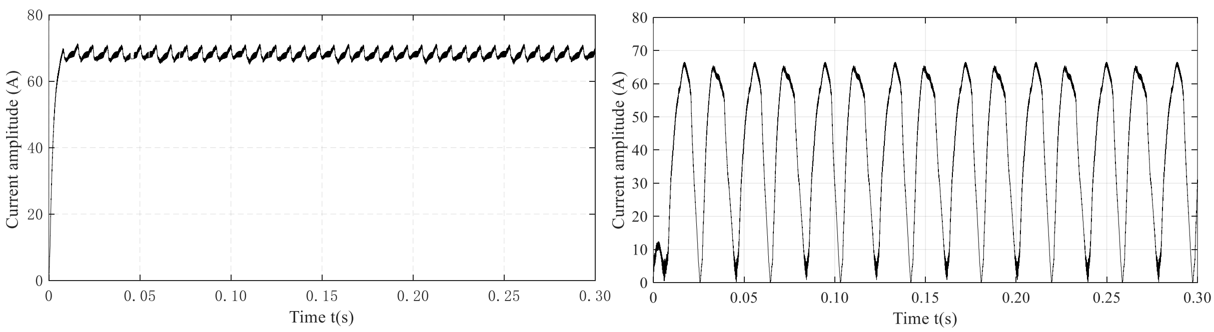


Figure 3 Fault-tolerant control mode



(a) Amplitude function image in healthy state (b) Amplitude function image in fault 16 state

Figure 4 Amplitude of current in normal and fault-16 states

4.2. IGBT open circuit fault location determination

Considering that the inverter power tube open circuit has a variety of fault modes, and the combination is more complicated, this paper selects fault 16 and fault 19 to simulate the situation of different faults occurring in the power tube, respectively, which is used to verify the superiority of the improved direct current method compared with the original method.

Figure 5 shows the current dwell time in the $\pi / 6$ and $7\pi / 6$ intervals for the fault 16 state and the other states. From the figure, it can be seen that the current phase dwell time in the $\pi/6$ and $7\pi/6$ intervals in the fault 16 state is significantly different as compared to the dwell time in the other states. After repeated tests, this method can accurately judge in the case of poor filtering conditions. It can normally work without tuning after changing the parameters of the inverter, which has strong stability and accuracy.

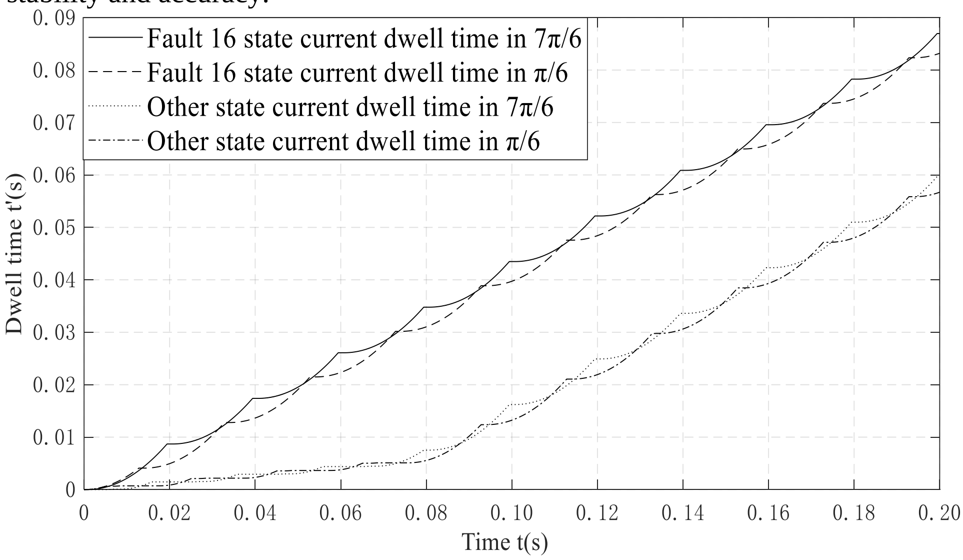


Figure 5 Amplitude function image in a healthy state

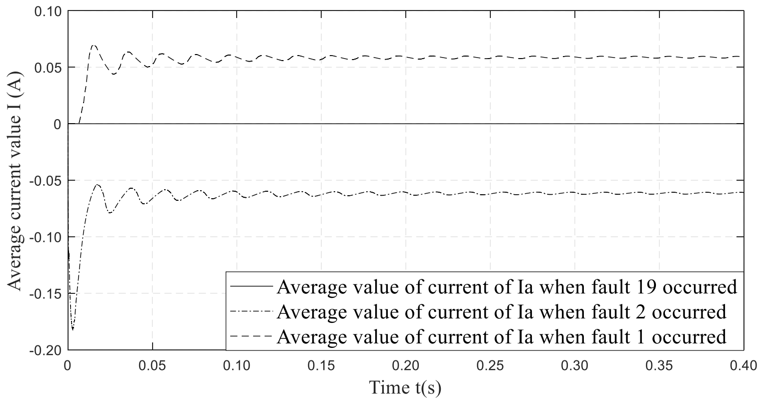


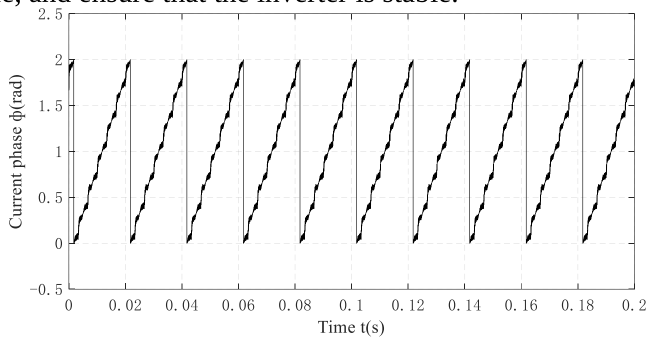
Figure 6 Amplitude function image in fault 16 state

$\theta s'$ is derived through the above method, then it can be used to complete the judgment of the fault 7-18, and because the fault 1, 2, 19, fault 3, 4, 20, fault 5, 6, and 21 of the same $\theta s'$, respectively, cannot be judged by alone, three currents Ia, Ib, Ic are necessary to be introduced to help to determine fault. Taking faults 1, 2, and 19 as an example. Figure 6 shows the average value of the current at faults 1, 2, and 19, and the results in the figure show that faults 1, 2, and 19 can be identified better by using Ia current. The remaining two groups of faults can be differentiated using a similar approach to introduce Ib and Ic for fault types. It is evident that Ia Ib and Ic can be used as criteria to distinguish three groups of faults and assist $\theta s'$ in the judgment of all fault types in single-phase and two-phase faults.

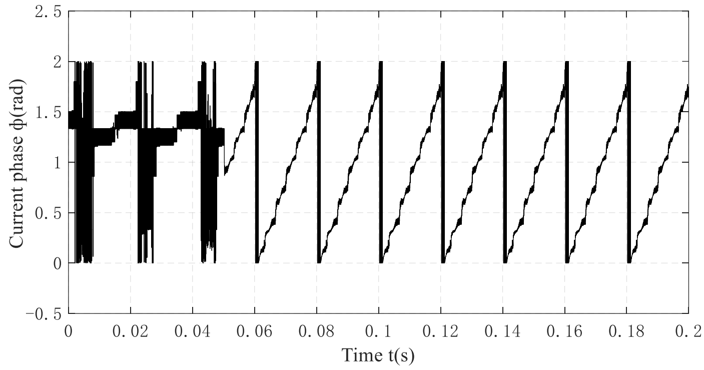
4.3. Fault tolerance model

In this paper, fault tolerance analysis is performed for fault 7, fault 16, fault 19, and health state 22 according to the fault tolerance model shown in Figure 3. The main idea of a fault-tolerant bridge circuit is: when fault 1 occurs, the status judgment signal outputs the fault signal and is allowed to output the fault-tolerant signal 1, which controls S1, S2, S3, S4, S5, SU, and SB to remain closed, S6, SD to open, and the modulating signal of T1 to TB, completing the process of connecting TB to the half-bridge where T1 is located and replace it, and the same for other faults.

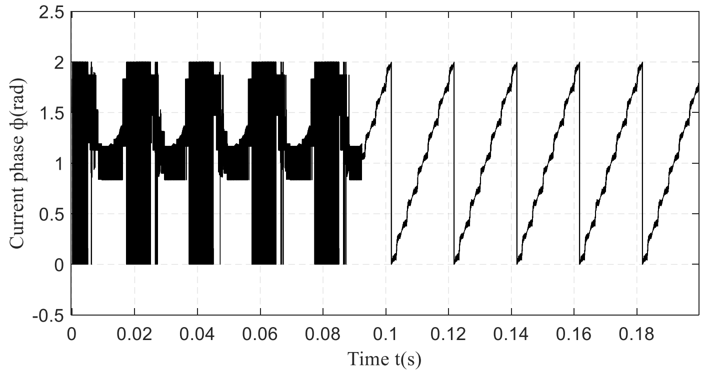
The fault tolerance results are shown in Figure. 7, where Figs. a, b, c, and d are examples of fault tolerance for healthy state 22, heterogeneous same side dual tube fault state 7, heterogeneous dual tube fault state 16, and single-phase dual tube fault state 19, respectively. The simulation results show that the model can quickly achieve fault tolerance for various types of open-circuit faults, keep the power tube current phase stable, and ensure that the inverter is stable.



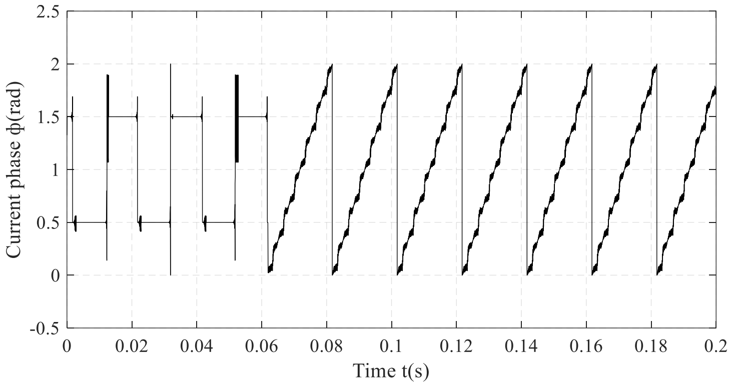
(a) Example of Health State22 Fault Tolerance



(b) Example of Fault State 7 Fault Tolerance



(c) Example of Fault State 16 Fault Tolerance



(d) Example of Fault State 19 Fault Tolerance

Figure 7 Examples of fault tolerance for health (22) and fault states (7,16,19)

5. Conclusion

In this research, a fault locating scheme for the three-phase full-bridge inverter is designed based on the direct current diagnosis method, and a bridge arm redundancy is adopted as its fault tolerance scheme. Then a fault tolerance model is built for simulation analysis for the power tube inverter open-circuit fault problem. The simulation results show that the method has the following advantages.

(1) Identifying whether the current amplitude can be descended to 0 by the direct current method can be used as the basis for judgment. It can better identify the power tube open circuit fault.

(2) The traditional direct current method of measuring the fault characteristic value is abandoned. The dwell time of the six phases described in the article is chosen as the basis for measuring the fault characteristic value. Then three currents are introduced to differentiate and accurately determine the 21 faults of the single and double-tube open circuit of power tubes.

(3) The redundant bridge arm design is used for fault-tolerant, which can quickly achieve fault tolerance for power tube open-circuit failures and is important for maintaining inverter stability.

Acknowledgments

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