A novel IGBT open-circuit protection method for three-phase PWM rectifier

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Abstract: In order to avoid the damage or the secondary fault caused by serious over-current, a new solution for protection of IGBT open-circuit faults in three-phase PWM rectifier is presented in this paper. Firstly, the open-circuit faults features of three-phase PWM rectifier have been analysed, and it was found that the most obvious features of open-circuit faults in three-phase PWM rectifier are the rise of some phase currents and the drop of DC voltage. Secondly, compared with the maximum and minimum absolute values of phase currents under normal state, one of them always can be 1.3 times larger than that of normal state when open-circuit faults occur in IGBTs except all IGBTs. Finally, by observing the DC voltage and the currents' behaviour, the maximum-minimum values-based method can detect the open-circuit faults of the system. The experiment results have verified that the method can effectively detect the open-circuit faults in IGBTs and protect the system.

Keywords: IGBT; open-circuit fault; protection method; three-phase PWM rectifier; statistical method.

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1 Introduction

Three-phase Pulse Width Modulation (PWM) rectifiers are widely employed in various fields, particularly in drives of electrical motors, control systems of battery charging and discharging, uninterruptible power supplies, etc. (Shi et al., 2018; Gui et al., 2018; Gonçalves et al., 2017). However, owing the complex operating conditions including atmospheric corrosion, humidness, temperature, and high electrical stress, three-phase PWM rectifiers are susceptible to unexpected faults such as short-circuit faults and open-circuit faults (Smet et al., 2011). Therefore, the stability of power electronic systems becomes more and more important.

According to the survey in Yang et al. (2011), Insulated Gate Bipolar Transistors (IGBTs) were the most used devices, and they are also one of the most vulnerable devices. IGBTs faults in three-phase PWM rectifiers are sub-divided into short-circuit and open-circuit faults (Li et al., 2015; Tinschert et al., 2016). Short-circuit fault will lead to an over-current, which is considered as the most dangerous. Nowadays, short-circuit detection and protections have been integrated into the hardware. When such a fault is detected, the driver will immediately turn off IGBT to protect the system and to ensure its safe shutdown (Youssef et al., 2017). The fast-acting fuses are used to isolate the short-circuit fault in Zeng et al. (2016), the fast-acting fuse is burned, and the rectifier can be regarded as in an open-circuit fault. Conversely, the equipped diode will continually work as a rectifier component when open-circuit faults occur in one or more IGBTs of the rectifier, however, open-circuit fault is also a threat to system, and much more time is necessary to detect it, and the performance will degrade causing output voltage fluctuation and current harmonics. It is likely to give rise to secondary fault of the equipment system with long-term faulty operation, resulting in higher maintenance costs. Therefore, it is necessary to detect the early features of open-circuit faults in IGBTs of three-phase PWM rectifier and to eliminate hidden dangers of insecurity in time (Rodrguez-Blanco et al., 2015).

At present, quite a few researches on open-circuit fault diagnosis in three-phase dc-ac inverter fed motor drives have been developed (Zhang et al., 2014; Jung et al., 2013; Yaghoubi et al., n.d.). A survey was presented in Lu and Sharma (2008) on existing methods for fault diagnosis and protection of IGBTs with special attention to those used in three-phase power inverter. Up to now, far too little attention has been paid to rectifier open-circuit fault diagnosis. In contrast to open-circuit fault diagnosis in inverter, the equipped diode will continually work as a rectifier component when open-circuit faults occur in one or more IGBTs and it generally does not cause the system shutdown but affect its performances such as non-sinusoidal current waveform and output voltages fluctuation. A real-time fault diagnosis method based on the primary inductances energy analysis for single and multiple transistors open-circuit faults was presented in Wu et al. (2017), when transistor open-circuit fault occurs in two-level three-phase boost rectifiers, the primary source inductances energy storage and release will be abnormal in some states for the reason that the primary source electrical circuit will be non-conductive due to connected diode reserve truncation. For the detection and isolation of open-circuit faults in voltage-source inverters feeding ac motors, a novel method was proposed in Sleszynski et al. (2009), and it was an extension of the normalised dc-components method, the normalised average currents were combined with additional diagnostic variables which convey information about the percentage of time spent by the phase currents in the near-zero zone.

The rectifier circuits of three-phase PWM rectifier are composed of switching devices, which are nonlinear devices. The existing mathematical model of three-phase PWM rectifier is obtained under the conditions of steady balance of three-phase parameters, no loss of switch tube and dc side capacitor without equivalent resistance, but the ac rectifier side current of the PWM rectifier under fault conditions is not consistent with the ideal mathematical model (Bryant et al., 2008; Xia et al., 2012). An accurate mathematical model was constructed in Rui et al. (2011), and the proposed model accurately described the fundamentals of the power rectifier in the post-fault operation. Nevertheless, the exact mathematical model was not enforceable to the design of system regulators because of its complexity. A fault detection and isolation method for open-circuit faults of power semiconductor devices in a modular multilevel converter was proposed in Shao et al. (2016), the proposed method is simple with only one sliding-mode observer equation and without additional transducers. However, the performance of the method is over-reliant on the accuracy of converter switching model.

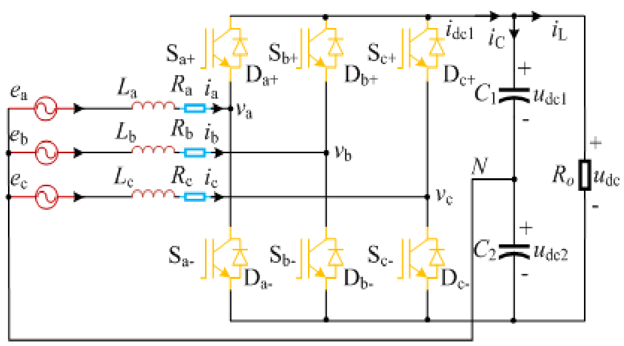
In recent years, the mathematical models of PWM rectifier are ideal models which are useful only under normal working condition and ideal conditions, but several studies under fault condition. Moreover, it is difficult to generalise and apply the mathematical model because the switching device is regarded as the ideal switching device. And meanwhile the static method is a commonly used existing approach (Cui et al., 2019a, 2019b). Therefore, this paper proposes a method that only needs to monitor the phase current and dc output voltage to realise fast fault identification and protection. By observing the dc voltage and the currents behaviour, the maximum-minimum values based method can detect the open-circuit faults of the system. The main advantage of this method is that the method can detect the faults easily without any knowledge of the system such as fault mathematical models, structures, or fault mechanisms. Finally the phase current and output voltage of three-phase PWM rectifier are monitored by hardware, and the experiments confirmed that the method can effectively detect the open-circuit faults in IGBTs and protect the system.

The paper is organised as follows: The experiments of IGBTs open-circuit faults in three-phase PWM rectifier are described in Section 2. The faults features of the maximum-minimum values and the proposed method are presented in details in Section 3. The fault protection experiments are presented in Section 4. Finally, conclusions are drawn in Section 5.

2 Experiment of IGBT open-circuit faults in three-phase PWM rectifier

The main circuit topology of three-phase PWM rectifier working as a rectifier is shown in Figure 1, where e_k is the source voltage, v_k is the input voltage of the rectifier bridge, i_k is the phase current, L_k is the filter inductance, R_k is the equivalent serial resistance, and $k = a, b, c$. C_1 and C_2 are the dc-link capacitances. In this paper, the Proportional-Resonant (PR) controller is used to complete the control of three-phase PWM rectifier, the control scheme of PR controller can be referred to Tang et al. (2012).

Figure 1 Main circuit topology of PWM rectifier



According to Ghosh and Narayanan (2008), it can be seen that the three-phase PWM rectifier is equivalent to three independent half bridge circuits. In this paper, i_a, i_b, i_c and u_{dc} are collected and analysed. Figure 2 is the experimental device of three-phase PWM rectifier. The upper computer software is used to control and turn off the control signals of IGBTs to simulate the open-circuit faults in IGBTs. The system used the real-time monitoring work state of the Field Programmable Gate Array (FPGA) controller, and set up security protect measures and fault processing function. The basic experimental parameters of three-phase PWM rectifier are shown in Table 1.

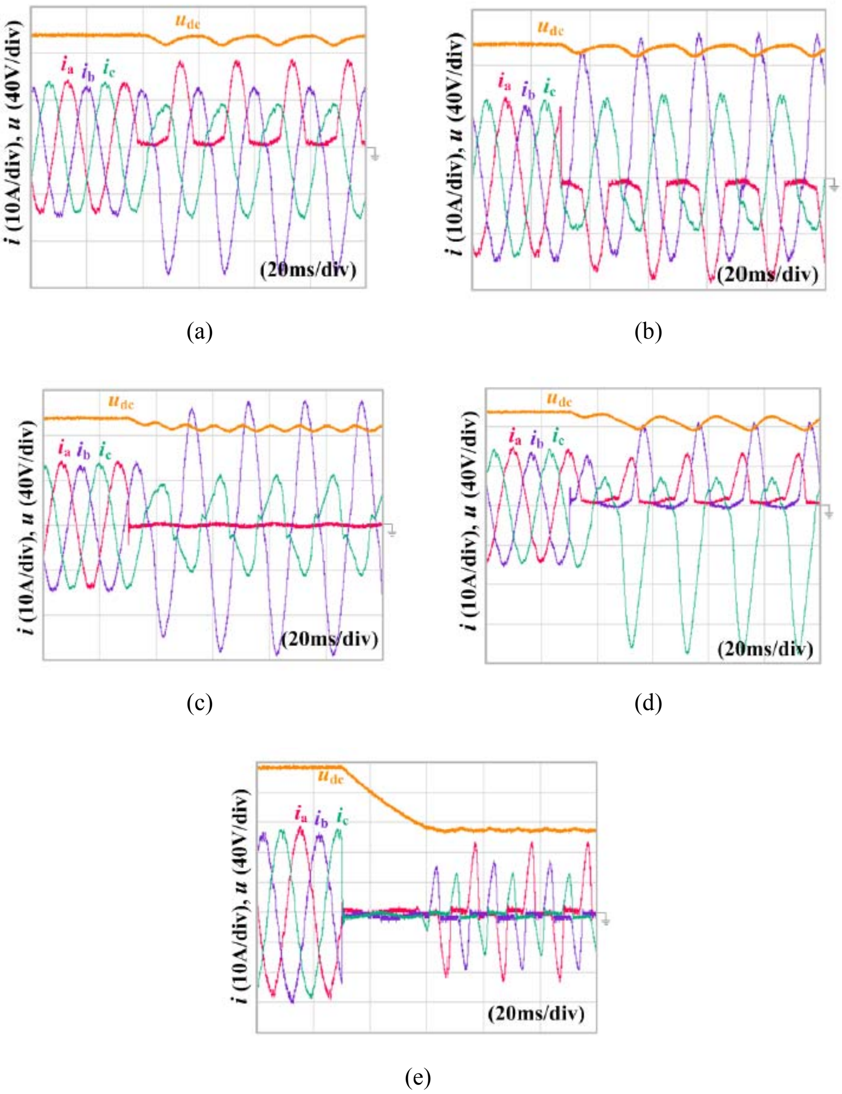
Figure 2 Experimental device of three-phase PWM rectifier

Table 1 Experimental parameter of three-phase PWM Rectifier

Parameter	*Value*
Input phase voltage	40 V
Grid voltages frequency	50 Hz
IGBT	FS1501212ET4
Switching frequency	12.8 kHz

Figure 3 is the experimental waveform of three-phase PWM rectifier when open-circuit faults occur in IGBTs. Figures 3(a) to 3(e) show the current and voltage waveforms when open-circuit faults occur in S_{a+}, S_{a-}, S_{a+} and S_{a-}, S_{a+} and S_{b+} or all IGBTs faults, respectively. It can be seen from the figure that when open-circuit faults occur in IGBTs, the equipped diode can continue to work as a rectifier element, and the system will not crash immediately. Compared with the amplitude of output voltage fluctuation and current harmonics in fault state, it is larger than that of normal states. Over the long term, such open-circuit faults may only make the underlying situation worse. Therefore, further studies need to be carried out in order to extract useful features for open-circuit faults protection.

Figure 3 Fault waveform of some IGBTs in three-phase PWM rectifier. (a) S_{a+} faults (b) S_{a-} faults (c) S_{a+} and S_{a-} faults (d) S_{a+} and S_{b+} faults (d) All IGBTs faults



3 Analysis of open-circuit faults features of three-phase PWM rectifier

Since the chance of double faults or more in different phases occurring simultaneously is very rare, diagnosis method considering single fault is enough in most applications. In this paper, the fault features of phase current and output voltage in three-phase PWM rectifier when open-circuit faults occur in single and two IGBTs are analysed.

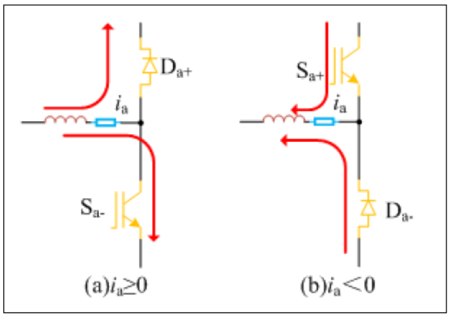
3.1 Open-circuit faults features

According to Table 2 and Figure 4, the current flows through different devices depending on the conditions. Taking the phase current i_a as an example, the ac current goes through S_{a-} and D_{a+} when $i_a \geq 0$, whereas it goes through S_{a+} and D_{a-} when $i_a 0$ (as shown in Figure 4). However, the fault IGBT keeps open-circuit and uncontrollable when an open-circuit fault occurs at IGBT S_{a+}. Therefore, the current path has changed in the negative half cycle and $S_a = 1$, which means that the upper arm is open and the lower arm is closed. The diodes D_{a-} turns from switch state to the non-freewheeling state in this case. Thus, when an open-circuit happens to S_{a+}, the current i_a is no longer controlled by the switch command, but depends on whether the diode is conducting.

Table 2 Operations of IGBTs and diodes in phase A

	$i_a \geq 0$	$i_a < 0$
$S_a = 1$	$D_{a+}ON$	$S_{a+}ON$
$S_a = 0$	$S_{a-}ON$	$D_{a-}ON$

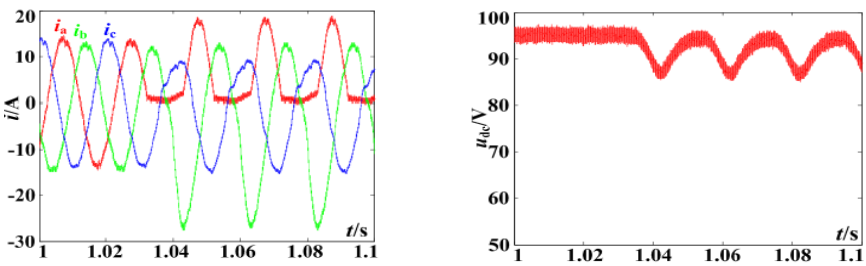
Figure 4 The current path of i_a



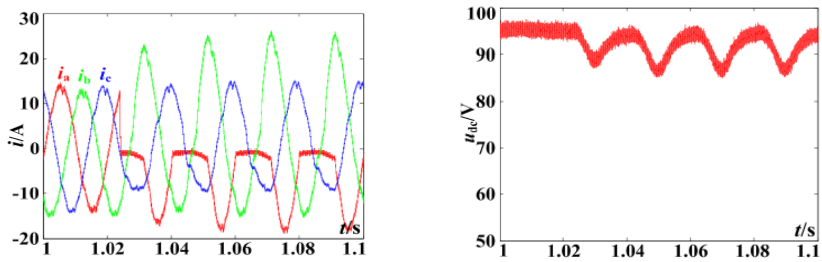
According to the above analysis, the open-circuit faults of three-phase PWM rectifier will cause phase current distortion. When an open-circuit occurs at S_{a+}, the topology of three-phase PWM rectifier is changed, the negative half cycle of phase current i_a is seriously affected in this case. However, the positive half cycle of phase current i_a is seriously affected in the case of an open-circuit occurs at S_{a-}. Figure 5 shows the phase currents and output voltage when there is a single IGBT fault. Figures 5(a) 5(b) show the currents and voltage when open-circuit occurs at S_{a+}. Figures 5(c) and 5(d) show the currents and voltage when open-circuit occurs at S_{a-}. The half cycle of the fault phase current which is seriously affected is approached to 0, and the other half cycle of the fault phase current's absolute value will increase more than that of normal state. The absolute value of non-fault phase current is more than twice that of the normal state, whereas the output voltage has a fluctuation with a downward trend.

Figure 6 shows the conditions when open-circuit faults occur in two IGBTs. Figures 6(a) and 6(b) show the currents and voltage when open-circuit occurs at S_{a+} and S_{a-}. Figures 6(c) and 6(d) show the currents and voltage when open-circuit occurs at S_{a-} and S_{a+}. Figures 6(e) and 6(f) show the currents and voltage when open-circuit occurs at S_{a+} and S_{b+}. However, the current has fluctuated more sharply at the same time. The amplitude fluctuation of DC output voltage also increases, and its downward trend is more obvious.

Figure 5 Phase current and output voltage when single IGBT fault (a) S_{a+} faults (a) S_{a+} faults (c) S_{a-} faults (d) S_{a-} faults

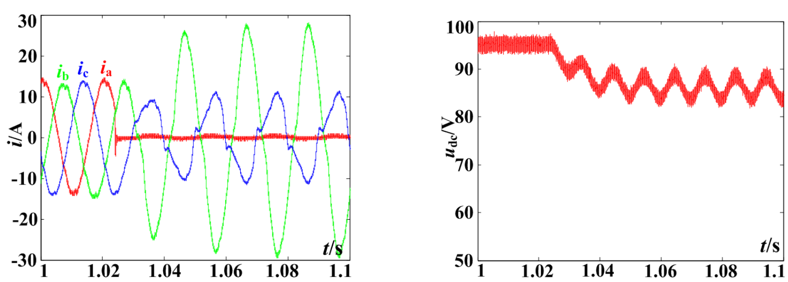


(a) (b)



(c) (d)

Figure 6 Phase current and output voltage when two IGBTs faults. (a) S_{a+} and S_{a-} faults (b) S_{a+} and S_{a-} faults (c) S_{a-} and S_{b+} faults (d) S_{a-} and S_{b+} faults (e) S_{a+} and S_{b+} faults (f) S_{a+} and S_{b+} faults



(a) (b)

Figure 6 Phase current and output voltage when two IGBTs faults. (a) S_{a+} and S_{a-} faults (b) S_{a+} and S_{a-} faults (c) S_{a-} and S_{b+} faults (d) S_{a-} and S_{b+} faults (e) S_{a+} and S_{b+} faults (f) S_{a+} and S_{b+} faults

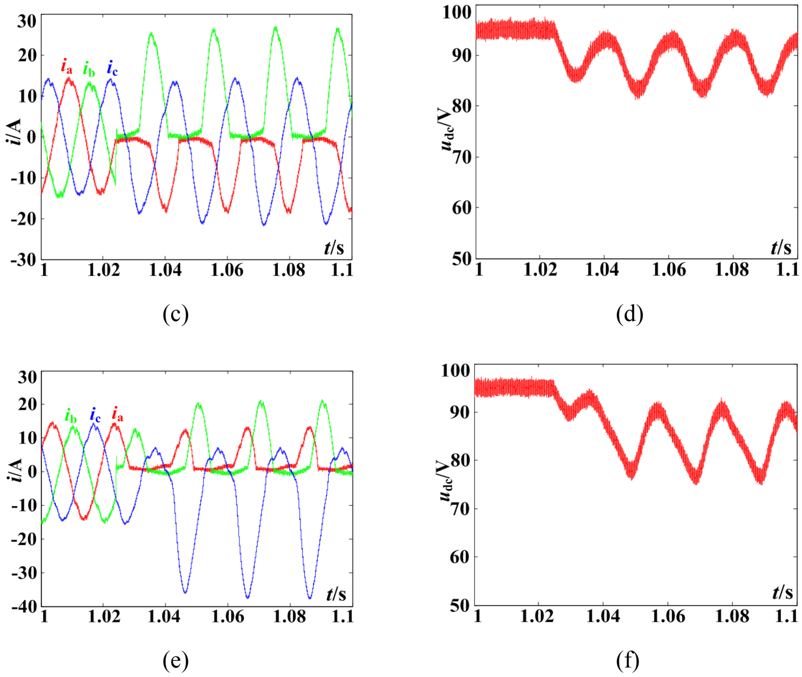
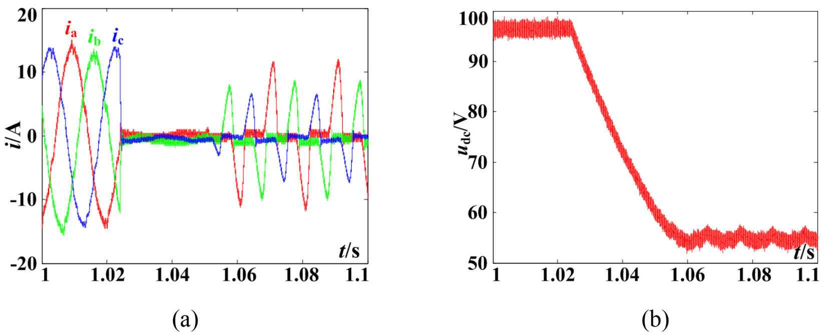


Figure 7 Phase current and output voltage when all IGBTs faults. (a) all IGBTs faults (b) all IGBTs faults



As shown in Figure 7, the rectifier has entered uncontrolled modes when open-circuit faults occur in all IGBTs. In a short period of time, all the currents change to zero and then enter a new stable state. There will be no over-current and the voltage will drop to the lowest state.

According to the above research, the rectifier works in controlled and uncontrolled mode alternately when open-circuit faults occur in some IGBTs, which is determined by the number and locations of fault IGBTs. Sometimes the value of the phase current is more than double that of the normal state. It is obvious that the rectifier will enter completely uncontrolled mode when open-circuit faults occur in all IGBTs. Therefore, the control signals of all IGBTs will shut down directly, once some open-circuit faults occur. In this case, the value of currents and voltage will be relatively safe.

3.2 Numerical analysis of fault features

Tables 3 and 4 show the numerical analysis of i_a, i_b, i_c, $i_a + i_b + i_c$, and u_{dc} when open-circuit faults happened in normal, S_{a+}, S_{a-}, S_{a+} and S_{a-}, S_{a-} and S_{b+}, S_{a+} and S_{b+} or all faults within one cycle, respectively. According to Tables 3 and 4, the maximum and minimum absolute values of i_a, i_b, i_c are about 14A under normal state. According to Tables 3 and 4, the maximum and minimum absolute values of i_a, i_b and i_c are about 14A under normal state. Compared with the maximum and minimum absolute values of i_a, i_b and i_c under normal state, some of them can be 1.3 times larger than that of normal state when open-circuit faults occur in IGBTs. While some of the maximums and minimums of i_a, i_b and i_c are increasing, the maximums and minimums of u_{dc} are decreasing. However, it may not trigger the protection circuit in this case. Also the thermal over-stress introduced by open-circuit faults on the semiconductor may bring about a short-circuit fault or other secondary faults. This may, in turn, lead to the shutdown of the overall system, and then the cost of fault can be enormous. For the safety considerations, the control signals of all IGBTs are blocked when the open-circuit faults occur. By this way, the rectifier can enter completely uncontrolled mode, and the current and voltage can re-enter a new steady state.

Table 3 Maximum values

	normal	S_{a+}	S_a	$S_a + S_{a-}$	$S_a - S_{b+}$	$S_a + S_{b+}$	*All faults*
i_a	14.65	18.96	0.04	0.99	0.33	13.95	12.32
i_b	13.32	12.99	25.94	27.56	26.90	21.25	8.67
i_c	14.21	9.47	15.23	10.90	14.47	7.14	6.90
$i_a + i_b + i_c$	1.58	10.26	14.55	17.87	11.43	15.69	11.88
u_{dc}	97.69	97.14	96.44	89.94	95.34	92.29	57.48

Table 4 Minimum values

	normal	S_{a+}	S_a	$S_a + S_{a-}$	$S_a - S_{b+}$	$S_a + S_{b+}$	*All faults*
i_a	–14.57	–0.29	–18.89	–0.99	–19.26	–0.33	–11.91
i_b	–14.91	–27.53	–14.91	–29.22	–0.99	–1.32	–10.25
i_c	–14.19	–15.35	–9.81	–11.06	–21.19	–37.30	–7.42
$i_a + i_b + i_c$	–3.37	–17.13	–12.95	–19.17	–20.94	–23.68	–13.88
u_{dc}	92.71	84.82	84.96	80.66	81.49	74.16	51.94

4 Protection experiment

The structure of three-phase PWM rectifier combined with fault protection unit is depicted in Figure 8, where the hardware circuit includes FPGA control unit, A/D module and so on, and the system parameters are consistent with the previous experimental parameters. In the system, the three-phase currents and dc output voltage of three-phase PWM rectifiers are used for the fault protection unit. It is useful to monitor the healthy condition of the rectifiers by reference to the three-phase currents and dc output voltage. On the one hand, the fault protection unit and the control system all make use of the three-phase currents and dc output voltage, and they are a unified whole. On the other hand, the fault protection unit is independent of the control system, it can be easy to insert into the control algorithm as a sub-routine without major modification. And three-phase currents and dc output voltage are employed to control system for generating drive signals to shut-down all IGBTs.

Figure 8 Structure of three-phase PWM rectifier with fault protection unit

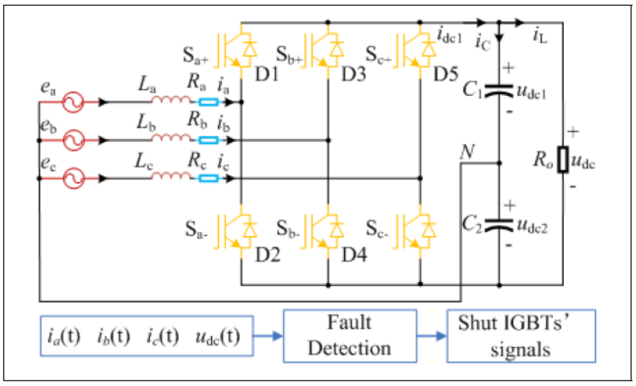
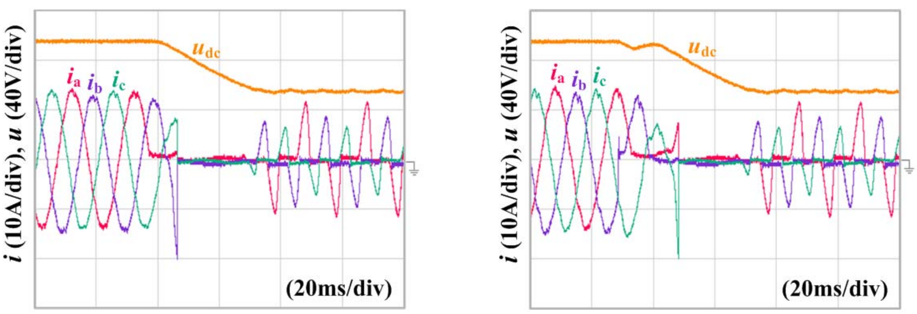


Figure 9 Fault protection experiment of three-phase PWM rectifier. (a) S_{a+} faults (b) S_{a+} and S_{b+} faults



(a) (b)

In order to verify the performance of the protection method, the experiments with various faults have been carried out. Take S_{a+} fault and (S_{a+} and S_{b+}) faults as examples to analyse. The currents and voltage of fault protection experiments are shown in Figure 9. As shown in Figure 9(a), when open-circuit fault happens in IGBT S_{a+}, the output voltage drops rapidly, and the current i_b is large. As shown in Figure 9(b), when open-circuit faults occur in IGBT S_{a+} and S_{b+}, the output voltage drops rapidly, meanwhile the current i_c is large. According to Figure 9, it can be seen that the control signals of all the IGBTs are shutdown when the output voltage drops rapidly and the current is larger than that of normal state, and the results show that the proposed protection method is suitable for three-phase PWM rectifier system.

5 Conclusions

The open-circuit faults features of three-phase PWM rectifier have been analysed, and it was found that the most obvious features of open-circuit faults in three-phase PWM rectifier are the rise of some phase currents and the drop of dc voltage. The proposed diagnosis method just requires the dc voltage and ac currents, which is convenient for hardware implementation.

Furthermore, by observing the dc voltage and the current's behaviour, the proposed method can detect the open-circuit faults of the system. By detecting the instantaneous distortion of ac currents and the dc voltage, the proposed method can detect the open-circuit faults rapidly as soon as they occur, and the effective fast and reliable fault protection method can shorten the fault isolation time. The sample rate is low, yet the method is simple but effective.

Finally, experiment results are presented, and the experiment cases have verified the feasibility of the proposed protection method. Once the open-circuit fault is detected, the fault protection unit will immediately turn off all IGBTs to protect the system and to ensure its safe shutdown.

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