Open-Switch Fault Diagnosis for Three-Phase AC-DC Power Converter with Park's Vector Method Considering Modulation Schemes

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Abstract—Open-switch fault accounts for large proportions among failures in power conversion system. Previously, fault deflection methods are carried out by researches from transient period or circuit configuration with complicated algorithms. This paper reveals characteristics of single IGBT open-switch fault in rectifier from perspective of modulation scheme. It presents that with a suitable modulation index and modulation scheme, current park's vector diagnosis method can become simple and effective for two-level three-phase AC-DC power converter. In that way, park's vector can be generalized for localizing faults in both inverter and rectifier.

Index Terms—AC-DC power converter, fault detection, IGBT open-switch fault, modulation scheme, generalized park's vector method, trajectories.

I. INTRODUCTION

Two-level three-phase AC-DC power converter is widely used among different industrial areas, such as wind power generation, electric vehicle and the like.

It is estimated that roughly 38% of unhealthy condition in power converter is due to semiconductor's failure and almost 70% of these faults was related to open circuit faults, short-circuit faults and gate-misfiring faults [1]. Short-circuit fault often happens during bond-wire rupture, gate-circuit degradation and over-current. The fault causes the whole system shutdown, even can destroy other peripheral devices. Basically, short-circuit can be detected through gate driver. Authors in [2] propose a method to locate short-circuit fault within one carrier period. In contrast, the system can still run under open-switch fault and can remain working for a period of time. At last, unhealthy working condition can cause overstress on IGBT, DC-link ripple and eventually lead to secondary fault after a period of abnormal operation, which also lead to secondary fault in power conversion system.

Several diagnosis methods for open-switch fault in voltage source inverter (VSI) have been investigated and developed

during the last decade [3]-[7]. However, less research work pays much attention to rectifier. Since phase current mainly flows through IGBT as an inverter while the main flowing path is freewheeling diode when it is used for rectifying. As a result, current park's vector patterns make inverter's diagnosis methods hard to be applied in AC-DC power converter. In [8], the method not only can locate single open-switch fault, but also can diagnose multiple open-switch fault. Actually, threshold value of inductance energy storage is not easy to choose. In [9], diagnosis method strictly depends on symmetrical circuit. Moreover, the diagnosis algorithm is complex, which imposes extra calculation burden on DSP, especially in high frequency power conversion applications. In [10], a modified current park's vector method needs at least two fundamental periods to detect fault. Besides, normalized DC current method is also sensitive to output power, which needs half cycle to detect fault. In [11], current angle detection method was presented. But, effectiveness of diagnosis is highly dependent on system parameter and output power. Authors in [12] proposed a method based on three-variable detection in PMSG drive system. More specifically, two different types of fault localization method are respectively used in grid-side and generator-side converter. It should be noted that low-pass filter is needed to be implemented, and also the experimental result is easily influenced by high-frequency noise. Model-based method proposed by authors in [13] can achieve multiple open-switch diagnosis.

Although these diagnosis methods are proposed for rectifier, few researchers take modulation schemes into consideration in open-switch fault condition. Hence, how modulation schemes impact faulty characteristics, and in turn whether it expands application scenarios of park's vector during the fault, comprehensive studies should to be carried out further.

The configuration of this paper is as follows. In Section II, the faulty characteristics under open-switch condition. In Section III, commutation periods during open-switch fault are analyzed. In Section IV, the influence of modulation schemes in open-switch fault is deeply investigated and generalized current park's vector method is proposed. The

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simulation results are shown in Section V. Conclusions are drawn in Section VI.

II. THE FAULTY CHARACTERISTICS UNDER OPEN-SWITCH CONDITION

Without loss of generality, VT1 is in open-switch fault in Fig.1, and unity power factor condition is considered for discussion. For inverter system, it can be showed in Fig.2(a) that pole voltage of faulty phase is positive while current is in its negative period. In that case, when VT1 fault occurs, freewheeling diode D2 cannot be conducted in a half-period. Unlike VSI, reference voltage and current vector have the same space position showed in Fig.2(b). In [11], the authors point out when composing V_{ref} in S2-2 and S5-2, phase-A current has a short zero-crossing period because D2 does not meet the conduction requirement. The characteristics of unhealthy phase current have been showed in [10]. More importantly, the authors present that specific interval is attributed to lower pole voltage compared with other poles, and negative current conducted by freewheeling diode is also influenced by output power and inductor value.

Additionally, only half-period phase current conduction during the fault can be observed in [14]. However, no more explanations in this paper. This is the basic phenomenon of single open-switch fault in two-level AC-DC power converter system discussed and studied by researchers for many years.

However, the fundamental mechanism of circulating current in freewheeling diode during open-switch fault is still unknown.

Fig.1. Topology of two-level three-phase AC-DC power converter.

Briefly, the pole voltage V_{UN} can determine conductivity of D2. Nevertheless, V_{UN} is a series of voltage pulse waveform, it is difficult to analyze its impact on freewheeling diode during a fundamental cycle. One of the applicable methods is the concept of modulation waveform which is the essence of SVPWM as well.

III. COMMUTATION PERIOD DURING OPEN-SWITCH FAULT

Since commutation period influences the faulty phase-current characteristics during open-switch fault, it is essential to analyze it with reference space voltage vector composing. Generally, PMSG-PWM rectifier system is showed in Fig.3.

(a)

(b)

Fig.2. The position of V_{ref} and I_s in SVPWM hexagon diagram for (a) inverter (b) rectifier.

Fig.3. PMSG-PWM rectifier system with VT1 open-switch fault.

When V_{ref} is needed to be synthesized in left half plane of hexagon (shadow area) in Fig.4., switching state of phase-A is always zero. The conduction of D2 can guarantee zero-state meanwhile phase-current is in its negative direction at that time. However, it must meet diode conduction requirement. Red and blue solid-line showed in Fig.3. correspond to phase-current in diode and IGBT, respectively. While red dash-line denotes possible faulty phase current direction.

Fig.4. Reachable area of hexagon during VT1 open-switch fault.

IV. THE INFLUENCE OF MODULATION SCHEMES IN OPEN-SWITCH FAULT

Through the analysis above, it can be seen that switching states impact current flowing direction in unhealthy condition. Since the modulation schemes are made up of different switching sequences. Hence, it is possible to be considered from modulation perspective.

A. Schematics of continuous SVPWM

Continuous SVPWM consists of two traditional modulation schemes: CSVPWM0 and CSVPWM1. The former switching sequence begins and ends up with switching state 000 and put 111 switching state in the middle, the latter begins and ends up with switching state 111 and put 000 switching state in the middle. The switching sequence with dwell time of CVPWM0 and CVSPWM1 can be showed in Fig.5.

In essence, SVPWM can be easily achieved when zero-sequence voltage component is injected into three-phase sinusoidal modulation signal. Therefore, modulation functions can be used to estimate the pole voltage among the three arms. V_{UO} can be defined as voltage between phase-A and neural-point of DC-link. Its mathematical function is expressed in (1).

Fig.5. Switching sequence in sector 1 based on (a) CVPWM0 (b) CVPWM1.

$$V_{UO} = \begin{cases} \frac{1}{2}MV_{dc} \cos(\theta - \frac{\pi}{6}) \\ \frac{\sqrt{3}}{2}MV_{dc} \cos \theta \\ \frac{1}{2}MV_{dc} \cos(\theta + \frac{\pi}{6}) \\ \frac{1}{2}MV_{dc} \cos(\theta - \frac{\pi}{6}) \\ \frac{\sqrt{3}}{2}MV_{dc} \cos \theta \\ \frac{1}{2}MV_{dc} \cos(\theta + \frac{\pi}{6}) \end{cases} = \frac{\sqrt{3}}{2}V_{ref} \begin{cases} \cos(\theta - \pi/6) & 0 < \theta < \pi/3 \\ \sqrt{3} \cos \theta & \pi/3 < \theta < 2\pi/3 \\ \cos(\theta + \pi/6) & 2\pi/3 < \theta < \pi \\ \cos(\theta - \pi/6) & 2\pi/3 < \theta < 4\pi/3 \\ \sqrt{3} \cos \theta & 2\pi/3 < \theta < 5\pi/3 \\ \cos(\theta + \pi/6) & 2\pi/3 < \theta < 2\pi \end{cases} \quad (1)$$

$$\Rightarrow \text{Min}(V_{UN}) = \text{Min}(V_{UO}) + V_{dc}/2 = (1-M)V_{dc}/2 \geq 0$$

Where M is modulation index, V_{VO} and V_{WO} can be attained by shifting V_{UO} with 120° and 240° , respectively. From (1), it can be seen that maximum and minimum value of V_{UO} both are $\pm MV_{dc}/2$ for CSVPWM0-1 scheme. Thus, $\text{Min}(V_{UN})$ can be calculated to define the minimum pole voltage of phase-U.

B. Schematics of discontinuous SVPWM

There are six discontinuous SVPWM, namely, DPWMMAX, DPWMMIN, DPWM0, DPWM1, DPWM2 and DPWM3, which are also known as 5-segment switching sequence[15]. The leg reference voltage for different modulation schemes are expressed from (2)-(7).

$$V_{UO} = \begin{cases} \frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{\pi}{6})] & \frac{\pi}{3} \leq \theta_0 \leq \pi \\ \frac{V_{dc}}{2} & -\frac{\pi}{3} \leq \theta_0 \leq \frac{\pi}{3} \\ \frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{5\pi}{6})] & -\pi \leq \theta_0 \leq -\frac{\pi}{3} \end{cases} \quad \text{DPWMMAX} \quad (2)$$

$$\Rightarrow \text{Min}(V_{UN}) = \text{Min}(V_{UO}) + V_{dc}/2 = (1-M)V_{dc} \geq 0$$

$$V_{UO} = \begin{cases} -\frac{V_{dc}}{2} & \frac{2\pi}{3} \leq \theta_0 \leq \pi \\ -\frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{5\pi}{6})] & 0 \leq \theta_0 \leq \frac{2\pi}{3} \\ -\frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{\pi}{6})] & -\frac{2\pi}{3} \leq \theta_0 \leq 0 \\ -\frac{V_{dc}}{2} & -\pi \leq \theta_0 \leq -\frac{2\pi}{3} \end{cases} \quad \text{DPWMMIN} \quad (3)$$

$$\Rightarrow \text{Min}(V_{UN}) = \text{Min}(V_{UO}) + V_{dc}/2 = 0$$

$$V_{UO} = \begin{cases} \frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{\pi}{6})] & \frac{2\pi}{3} \leq \theta_0 \leq \pi \\ -\frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{5\pi}{6})] & \frac{\pi}{3} \leq \theta_0 \leq \frac{2\pi}{3} \\ \frac{V_{dc}}{2} & 0 \leq \theta_0 \leq \frac{\pi}{3} \\ -\frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{\pi}{6})] & -\frac{\pi}{3} \leq \theta_0 \leq 0 \\ \frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{5\pi}{6})] & -\frac{2\pi}{3} \leq \theta_0 \leq -\frac{\pi}{3} \\ -\frac{V_{dc}}{2} & -\pi \leq \theta_0 \leq -\frac{2\pi}{3} \end{cases} \quad \text{DPWM0} \quad (4)$$

$$\Rightarrow \text{Min}(V_{UN}) = \text{Min}(V_{UO}) + V_{dc} / 2 = 0$$

$$V_{UO} = \begin{cases} \frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{\pi}{6})] & \frac{5\pi}{6} \leq \theta_0 \leq \pi \\ -\frac{V_{dc}}{2} & \frac{2\pi}{3} \leq \theta_0 \leq \frac{5\pi}{6} \\ -\frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{5\pi}{6})] & \frac{\pi}{2} \leq \theta_0 \leq \frac{2\pi}{3} \\ \frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{\pi}{6})] & \frac{\pi}{3} \leq \theta_0 \leq \frac{\pi}{2} \\ \frac{V_{dc}}{2} & \frac{\pi}{6} \leq \theta_0 \leq \frac{\pi}{3} \\ -\frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{5\pi}{6})] & 0 \leq \theta_0 \leq \frac{\pi}{6} \\ -\frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{\pi}{6})] & -\frac{\pi}{6} \leq \theta_0 \leq 0 \\ \frac{V_{dc}}{2} & -\frac{\pi}{3} \leq \theta_0 \leq -\frac{\pi}{6} \\ \frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{5\pi}{6})] & -\frac{\pi}{2} \leq \theta_0 \leq -\frac{\pi}{3} \\ -\frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{\pi}{6})] & -\frac{2\pi}{3} \leq \theta_0 \leq -\frac{\pi}{2} \\ -\frac{V_{dc}}{2} & -\frac{5\pi}{6} \leq \theta_0 \leq -\frac{2\pi}{3} \\ \frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{5\pi}{6})] & -\pi \leq \theta_0 \leq -\frac{5\pi}{6} \end{cases} \quad \text{DPWM1} \quad (5)$$

$$\Rightarrow \text{Min}(V_{UN}) = \text{Min}(V_{UO}) + V_{dc} / 2 = 0$$

$$V_{UO} = \begin{cases} \frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{\pi}{6})] & \frac{2\pi}{3} \leq \theta_0 \leq \pi \\ -\frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{5\pi}{6})] & \frac{\pi}{3} \leq \theta_0 \leq \frac{2\pi}{3} \\ \frac{V_{dc}}{2} & 0 \leq \theta_0 \leq \frac{\pi}{3} \\ -\frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{\pi}{6})] & -\frac{\pi}{3} \leq \theta_0 \leq 0 \\ \frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{5\pi}{6})] & -\frac{2\pi}{3} \leq \theta_0 \leq -\frac{\pi}{3} \\ -\frac{V_{dc}}{2} & -\pi \leq \theta_0 \leq -\frac{2\pi}{3} \end{cases} \quad \text{DPWM2} \quad (6)$$

$$\Rightarrow \text{Min}(V_{UN}) = \text{Min}(V_{UO}) + V_{dc} / 2 = 0$$

C. Analysis of open-switch fault considering modulation schemes

From equation (3)-(7), when using DPWMMIN, DPWM0, DPWM1, DPWM2 and DPWM3 during open-switch fault in VT1, the minimum modulation voltage V_{UN} between anode and cathode is zero, so commutation period

$$V_{UO} = \begin{cases} -\frac{V_{dc}}{2} & \frac{5\pi}{6} \leq \theta_0 \leq \pi \\ \frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{\pi}{6})] & \frac{\pi}{2} \leq \theta_0 \leq \frac{5\pi}{6} \\ -\frac{V_{dc}}{2} [1 + 2M \cos(\theta_0 + \frac{5\pi}{6})] & \frac{\pi}{6} \leq \theta_0 \leq \frac{\pi}{2} \\ \frac{V_{dc}}{2} & -\frac{\pi}{6} \leq \theta_0 \leq \frac{\pi}{6} \\ -\frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{\pi}{6})] & -\frac{\pi}{2} \leq \theta_0 \leq -\frac{\pi}{6} \\ \frac{V_{dc}}{2} [1 - 2M \cos(\theta_0 + \frac{5\pi}{6})] & -\frac{5\pi}{6} \leq \theta_0 \leq -\frac{\pi}{2} \\ -\frac{V_{dc}}{2} & -\pi \leq \theta_0 \leq -\frac{5\pi}{6} \end{cases} \quad \text{DPWM3} \quad (7)$$

$$\Rightarrow \text{Min}(V_{UN}) = \text{Min}(V_{UO}) + V_{dc} / 2 = 0$$

can be easily completed through freewheeling diode D2.

However, for CSVPWM0, CSVPWM1 and DPWMMAX, V_{UN} is related to modulation index (MI) and reference DC-link voltage (V_{dc}). Because according to the definition of MI defined by (8). DC-link voltage is also one part of it. When MI is not high enough, D2 is reverse truncation. In this circumstance, current park's vector method can be used to diagnose under CSVPWM0, CSVPWM1 and DPWMMAX scheme.

$$MI = \frac{\sqrt{3}V_{ref}}{V_{dc}} \quad (8)$$

The space vector diagram with unity power factor can be depicted in Fig.6., voltage drop on resistance is neglected due to small value. From this diagram, it can be found that MI is also associated with the inductor value. Through the analysis above, it may explain the reason that system parameters can influence faulty phenomena described in [5].

Modulation waveform can be observed from pole voltage by adding a low-pass filter in Fig.7 where V_{dc} is set to 500V and MI is 0.62. The minimum voltage value of modulation waveform can be marked with orange dotted-line in which $(1-M)V_{dc}/2$ and $(1-M)V_{dc}$ are 95V and 190V, respectively.

Fig.6. Space voltage vector diagram with unity power factor.

Fig.7. Modulation waveform with different schemes (a)CSVPWM0 (b)CSVPWM1 (c)DPWM0 (d)DPWM1 (e)DPWM2 (f)DPWM3 (g)DPWMMAX (h)DPWMMIN.

V. SIMULATION RESULTS OF OPEN-SWITCH FAULT DETECTION

A. Three-phase current before and after open-switch fault

If open-switch fault in VT1 occurs at 0.6s, three-phase voltage and current can be showed in Fig.8 when using CSVPWM0, CSVPWM1 and DPWMMAX with different MI. It can be seen from Fig.8.(c)-(e) that phase-U current only has positive period.

Fig.8. Three-phase voltage and current before and after fault by using CSVPWM0, CSVPWM1 and DPWMMAX with MI at (a) 0.98 (b) 0.9 (c) 0.8 (d) 0.7 (e) 0.6.

Fig.9. Three-phase voltage and current before and after fault by using DPWM0-3 and DPWMMIN with MI at (a) 0.98 (b) 0.9 (c) 0.8 (d) 0.7 (e) 0.6.

Similarly, for the rest of modulation schemes, unhealthy phase current can be obtained in Fig.9. under the same conditions. From the analysis and current waveform showed above, it can be concluded that the phase-A current cannot be blocked in its negative period within all range of MI.

B. Generalized current park's vector trajectories based on different modulation schemes

The current-park's vector diagram under single open-switch fault of VT1, VT3 and VT5 in each arm can be showed in Fig.10, respectively. Current park's vector diagram is a half-circle with CSVPWM, CSVPWM1 and DPWMMAX schemes in which MI is not high enough to guarantee conductivity of freewheeling diode. The edge angle of half-circle can be used to locate the fault. For example, 90° , 210° and 330° are the edge angle of park's vector trajectory for faulty VT1, VT3 and VT5, respectively. It can be seen that one fundamental period fundamental period is needed to detect the fault.

Fig.10. Current-park's vector diagram with CSVPWM0, CSVPWM1 or DPWMMAX during open-switch fault in (a) VT1 (b) VT3 (c) VT5.

By contrast, current patterns of other modulation schemes are ineffective and independent with MI. The trajectory of the park's vector become irregular shape and is totally degraded. An example by using DPWM3 scheme with faulty VT1 is illustrated in Fig.11.

Fig.11. Current-park's vector diagram with DPWM3 during open-switch fault in VT1.

The simulation results show the consistency of mathematical analysis discussed in Section-IV. Park's vector is still exceptionally applicable for diagnosis of open-switch fault in relatively low modulation applications with special modulation schemes.

VI. CONCLUSION

From perspective of modulation scheme, single open-switch fault in two-level power converter is investigated and analyzed. The effectiveness of the diagnosis method is well studied with a suitable modulation index and CSVPWM0, CSVPWM1 or DPWMMAX modulation scheme. It can be found that modulation scheme has a tight relationship with

TABLE I
THE COMPARISON WITH PREVIOUS DIAGNOSIS METHODS

Diagnosis Method	Detection Time	Robustness	Sensitive to System Parameters	Generality
Modified Park's vector method	>2 cycles	Low	Low	Rectifier
Current zero-crossing detection method	0.25 cycle	Low	Low	Rectifier
Three diagnostic variables method	0.1 cycle	Low	High	Rectifier
Model-based method	0.25 cycle	High	High	Rectifier/Inverter
Current similarity analysis-based method	0.25 cycle	High	Low	Rectifier
Inductance energy analysis-based method	0.25 cycle	High	Low	Rectifier
Generalized current Park's vector method	1 cycle	High	Low	Rectifier/Inverter

commutation of freewheeling diode, thereby resulting in different current patterns. Most importantly, generalized current park's vector method can be unified for single open-switch detection in both rectifier and inverter system.

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