Diagnosis Methods for IGBT Open Switch Fault Applied to 3-Phase AC/DC PWM Converter

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Abstract

Fault diagnosis technique of electrical drives is becoming more and more important, since voltage fed converter system has become industrial standard in many applications. Many studies have been conducted an inverter fault diagnosis for induction motors. However, there are few researches about fault diagnosis of 3-phase ac/dc PWM (Pulse Width Modulation) converter compared to the dc/ ac inverter. The ac/dc converter is the opposite of dc/ac inverter at current flow. Also, inverter and converter have different current patterns under the same condition of IGBT (Insulated gate bipolar transistor) open switch fault. Therefore, it is difficult to apply intact diagnosis methods of inverter to the converter. This paper proposes modified fault detection methods for IGBT open switch fault in 3-phase ac/dc PWM converter by modifying established fault diagnostic methods for dc/ac inverters.

Key Words: Converter, Diagnosis, Fault detection, Normalized DC Current Method, Open switch fault, Park's Vector Method

I. INTRODUCTION

In recent years, 3-phase ac/dc PWM converter has become the standard in industrial applications due to its advanced features which include sinusoidal input current with unity power factor and high-quality dc output voltage [1]. The reliability of the power conversion systems have been always important issue. So, fault diagnostic methods of the system are required to improve reliability and guarantee scheduled maintenance. It is estimated that about 38% of the faults in voltage-source power conversion system are due to failures of power devices such as IGBT. Its failures can be broadly categorized as short circuit faults and open switch faults [2].

Short circuit faults are caused by bond wire rupture, impact ionization, gate circuit degradation and over- current [3]. Short circuit faults cause system shutdown because its source is blocked by protection circuits which include circuit breaker and fuses. Otherwise, the system is critically destroyed with damages incurred switching and peripheral device. Therefore, protection circuits are the most critical components that prevent the destabilization of the whole system after short circuit faults occur.

On the other hand, open switch faults can be caused either by device driver failures, the rupture of the connections induced by over-heating, or the lift of bonding wire resulting from thermic cycling [4]. Open switch faults of the system do not cause system shutdown contrary to short circuit faults, but degrades its performance. Such degradations in return represent the source of secondary faults. If such state of abnormal operation lasts for extended period of time, accumulated fatigue under unstable operation may generate malfunctions in several devices of the system. Accordingly, there is high probability of secondary faults occurrence in the load, grid, and converter system. Therefore, diagnostic techniques of power conversion systems are required for monitoring and detecting of open switch faults.

Some diagnosis methods of open switch fault in dc/ac inverter have been developed during the last decade by Mendes, Abramik, Peuget and others [5]–[10]. Most of these fault diagnostic methods for inverters were reviewed by Bin Lu [11], [12]. However, there are only few researches done on fault diagnosis of 3-phase ac/dc PWM converter. The ac/dc converter is the opposite of dc/ac inverter at current flow. Also, they have different current patterns each other under the same condition of IGBT open switch fault. Therefore, it is difficult to apply the same kind of diagnosis methods used for inverter to the converter.

This paper proposes modified fault detection method for IGBT open switch fault in 3-phase ac/dc PWM converter by modifying established fault diagnostic methods for dc/ac inverters. First of all, a comparison of IGBT open switch fault is shown in inverter and converter. Then, established fault diagnosis methods of Mendes and Abramik are applied in ac/dc converter. Subsequently, the modified fault diagnosis methods are proposed. Finally, the experimentations are performed to verify the proposed methods.
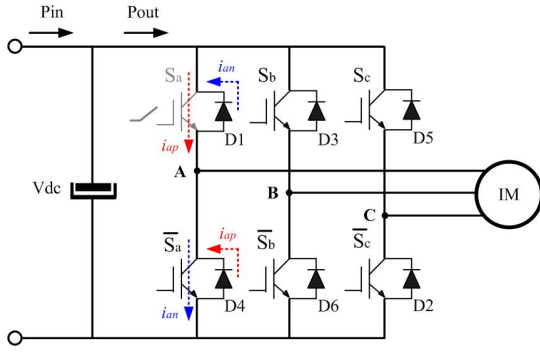
Fig. 1. 3-phase PWM inverter (S_a open).
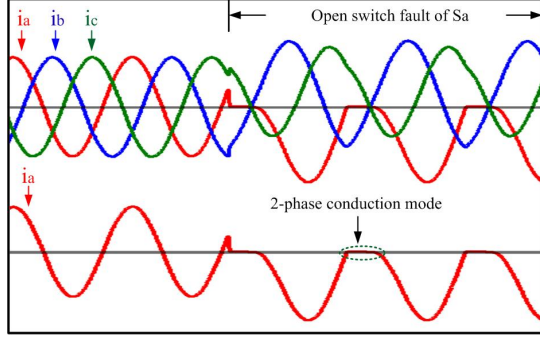
Fig. 2. Phase currents in S_a open fault of inverter.

Fig. 3. 3-phase ac/dc PWM converter (S_a open).

Fig. 4. Phase currents in S_a open fault in ac/dc converter.

II. COMPARISON OF IGBT OPEN SWITCH FAULT IN INVERTER AND CONVERTER
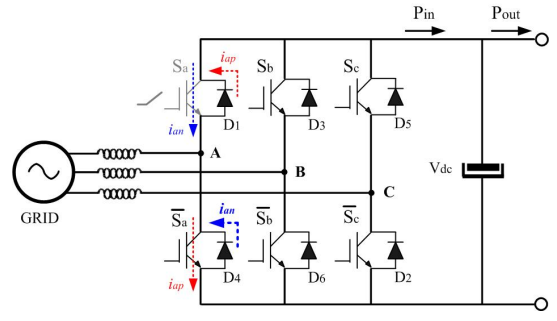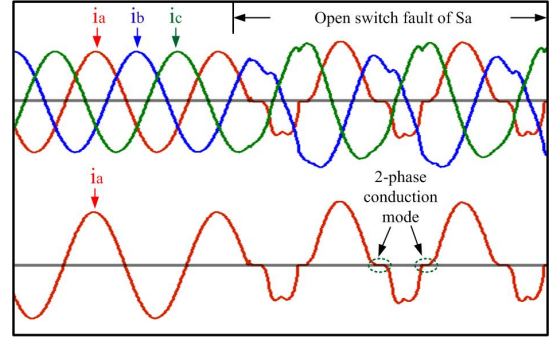
A. IGBT Open Switch Faults in DC/AC Inverter

In IGBT open faults of dc/ac inverter, a faulty phase current can either be positive or negative depending on the damaged switch. Fig. 1 shows a configuration of 3-phase PWM inverter and induction motor. The i_{ap} and i_{an} are positive and negative current in a-phase, respectively. If IGBT open switch fault in S_a occurs during normal operation as shown in Fig. 1, phase current waveforms of Fig. 2 are appeared. After the fault of S_a, a-phase has only the negative current because the faulty switch S_a cannot conduct any current as shown in Fig. 2. The freewheeling diode D_4 in Fig. 1 also cannot conduct any current because A-pole voltage is higher than other two poles. The other phase currents operate 2-phase conduction mode while a-phase current is zero.

B. IGBT Open Switch Faults in AC/DC Converter

Phenomenon of IGBT open switch fault in ac/dc converter has a big difference compared to the one in ac/dc inverter. Fig. 3 shows a configuration of 3-phase ac/dc PWM converter with a fault in S_a indicated by an open gate connection. Fig. 4 shows phase current waveforms before and after IGBT open switch fault of S_a. Contrary to inverter, a-phase current has both positive and negative value.

As shown in Fig. 3, the positive current of a-phase conducts through $\overline{S_a}$ and D_1, and the negative current of a-phase conducts through S_a and D_4. Therefore, the open fault of switch S_a does not affect the positive current of the ac/dc converter as shown in Fig. 4. However, the fault causes the block of the negative current through S_a. So, 2-phase conduction mode of Fig. 4 is represented. Then, unlike the inverter, negative current is generated during specific interval as shown in Fig. 4. It is because freewheeling diode D_4 is conducted when A-pole voltage is lower than the other poles.

As shown in Fig. 4, the shape of the distorted a-phase negative current resembles the current of 3-phase rectifier. However, the shape is not always the same. As shown in Fig. 5, the shapes are various according to the control performance, reactor capacity, load power and reference DC-link voltage.

In general, the high performance converter is operated by symmetrical SVPWM (Space Vector PWM) and digital PI (Proportional Integral) controller. All gains of PI controller relate to the control performance so that current shapes are a little different. It follows that reactor capacity not only relates to the proportional gain of PI current controller but also determines the slope of the current. As a result, the resulting waveforms in faulty condition differ from each other according to the reactor capacity as shown in Fig. 5. If load power is high, the input currents are large. Hence, the circulating current through freewheeling diode D_4 is also increased in S_a fault condition. As shown in Fig. 5, the higher load power, the larger the negative current will become. Fig. 6 illustrates different outcomes resulting from the change of DC-link voltage reference. In S_a open switch fault, the zero vector of (1,1,1) cannot be available due to the faulty switch. Instead of the zero vector, it acts as active vector (0,1,1). Therefore, the current is distorted by zero vector size of (1,1,1). The higher the reference DC-link voltage, the longer the zero vector time becomes in SVPWM. Accordingly, if the DC-link voltage reference gets high enough, the current tends to deteriorate under the open switch fault condition.

In addition, Fig. 6 also shows PWM switching patterns before and after open switch fault. The switching patterns are distorted due to the abnormal vectors related switch S_a.
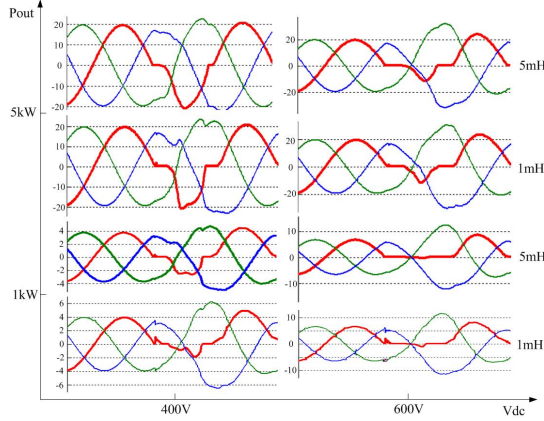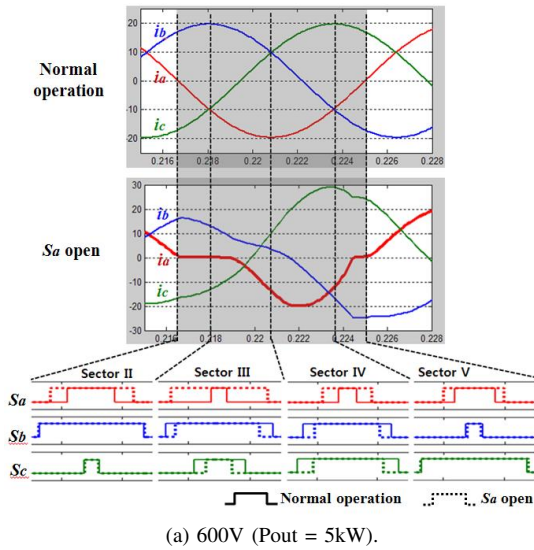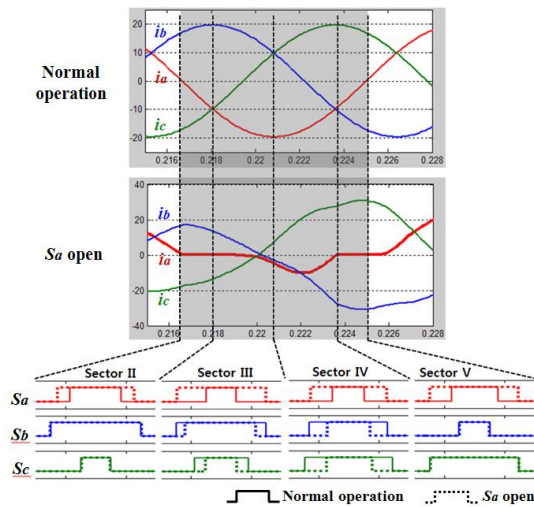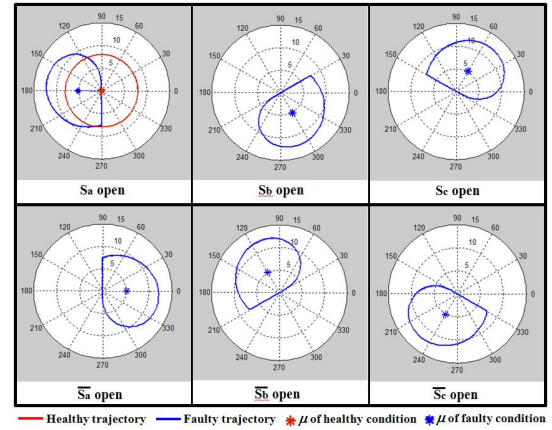
Fig. 5. Shapes of distorted current (S$_a$ open).

(a) 600V (Pout = 5kW).

(b) 400V (Pout = 5kW).

Fig. 6. Effect of the change in DC-link voltage reference.

Fig. 7. μ and dq-current trajectories under open switch fault condition of inverter.

III. AN APPLICATION OF EXISTING INVERTER METHODS FOR AC/DC PWM CONVERTER

It is difficult to apply the same kind of diagnosis methods used for inverter to the converter because of aforementioned differences between ac/dc converter and dc/ac inverter. Therefore, this paper suggests application methods through modifications of exiting Park's Vector Method and Normalized DC Current Method.

A. An application of Park's Vector Method

Park's Vector Method [7] takes advantage of an average value of d- and q-axis currents during one cycle. 3-phase phase currents can be transformed to the 2-phase dq-currents by Park's Vector transformation of (1). Then, the averages during one cycle in dq-currents are calculated by (2). The obtained two average values can be expressed as one point μ on dq-coordinate by (3).

$$i_d^s = \frac{2}{3}i_a^s - \frac{1}{3}(i_d^s + i_c^s) \ , \ i_q^s = \frac{1}{\sqrt{3}}(i_b^s - i_c^s) \qquad (1)$$

$$\mu_x = \frac{1}{N}\sum_{k=1}^{N} i_x(k\tau) \qquad (2)$$

$$\mu = \mu_d + j\mu_q = M_\mu \angle \theta_\mu$$
$$M_\mu = \sqrt{(\mu_d)^2 + (\mu_q)^2} \ , \ \theta_\mu = \tan^{-1}\frac{\mu_q}{\mu_d}. \qquad (3)$$

Fig. 7 shows dq-current trajectories and point μ under each open switch fault condition. First cell of Fig. 7 is result of Fig. 2. In normal operation, the trajectory and average point are a circle and an origin, respectively. But, they are a half circle and a biased point in left half-plain under the S$_a$ open fault condition. Faults of the other switches appear shapes rotated by 60 degrees as shown in Fig. 7. So, the biased point μ can be a standard for open fault detection. Therefore, Park's Vector Method can find the switch of the open fault from the argument of the point when the magnitude of μ exceeds a certain threshold value as shown in Table I.

If Park's Vector method applies to ac/dc converter, the results are shown in Fig. 8. First cell of Fig. 8 is result of Fig. 4. The half circle is reversed by 180 degrees compared to Fig. 7. However, it does not need to be considered due to
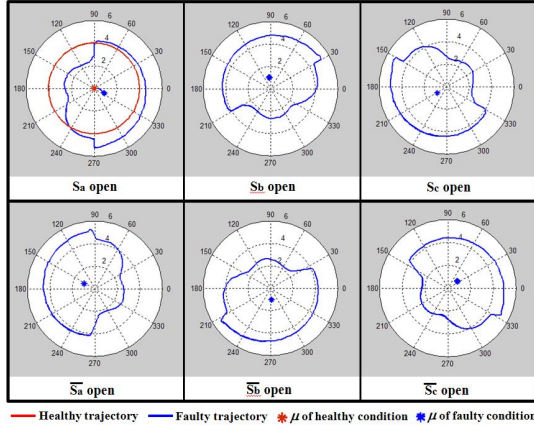
Fig. 8. μ and dq-current trajectories under open fault condition of ac/dc converter.

TABLE I
LOCALIZATION OF FAULT WITH PARK'S VECTOR METHOD IN DC/AC INVERTER

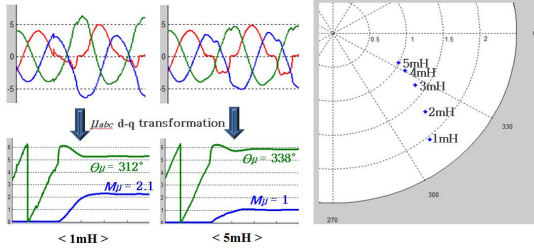| Open Switch	Magnitude μ	Interval of θ_μ
Sa		$150 < \theta_\mu < 210$
$\overline{Sa}$		$330 < \theta_\mu < 30$
Sb	Exceed Threshold	$270 < \theta_\mu < 330$
$\overline{Sb}$		$90 < \theta_\mu < 150$
Sc		$30 < \theta_\mu < 90$
$\overline{Sc}$		$210 < \theta_\mu < 270$

Fig. 9. The detected point of μ according to installed reactor in case of S_a open fault.
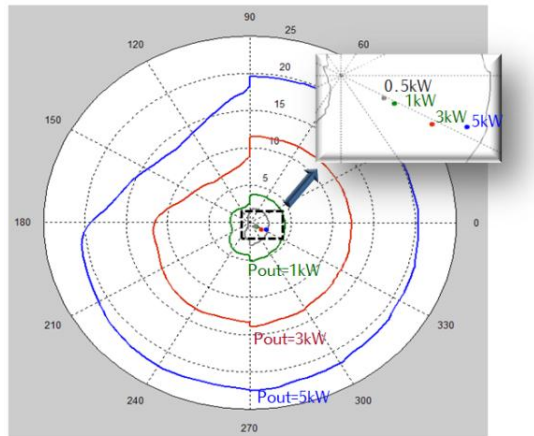

Fig. 10. The detected point of μ according to load power in open fault of S_a.

TABLE II
PROPOSED LOCALIZATION OF FAULT WITH PARK'S VECTOR METHOD IN AC/DC CONVERTER

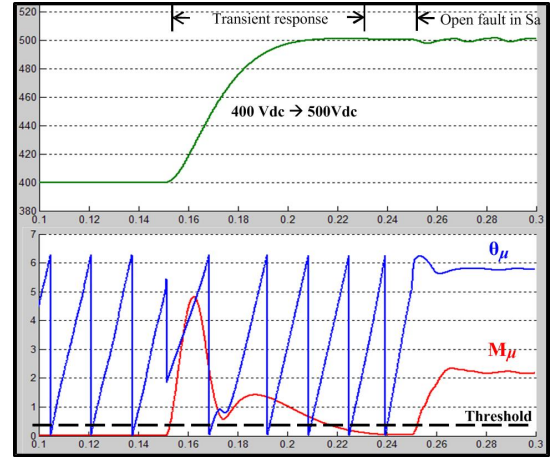| Open Switch	Magnitude μ	Interval of θ_μ
Sa		$300 < \theta_\mu < 0$
$\overline{Sa}$		$120 < \theta_\mu < 180$
Sb	Exceed Threshold	$60 < \theta_\mu < 120$
$\overline{Sb}$		$240 < \theta_\mu < 300$
Sc		$180 < \theta_\mu < 240$
$\overline{Sc}$		$0 < \theta_\mu < 60$

Fig. 11. Transient state and fault detection in modified Park's Vector Method.

the difference in direction of current sensor. But converter has both positive and negative current so that μ is smaller than it of inverter. Also, the argument is rotated by small amount because the trajectory is biased to one side. In addition, Fig. 9 shows various μ points according to the reactor capacity. As mentioned earlier, reactor capacity affects the control performance and the slope of current so that magnitude and argument of μ are varied at the same time similarly to Fig. 9. Fig. 10 shows the trajectories and μ points according to the load power. The higher power load, the larger magnitude μ becomes. As a result, the threshold of converter for the fault detection should be smaller than the threshold of inverter. Also, the localized θ_μ should be rotated by 30 degrees as shown in Table II.

As shown in Fig. 11, magnitude of μ can exceed the threshold value at the transient state – i.e. the change of the load or reference voltage. Also, transient time of μ in open switch fault is smaller than transient time of voltage change. Therefore, the level of certainty of open switch fault can be decided after threshold value exceeds maximum transient time. The algorithm that considers transient state can be represented in the flowchart of Fig. 12.

B. An application of Normalized StateDC Current Method

Normalized DC Current Method [8] developed by Abramik also uses the direct component μ of the phase currents through
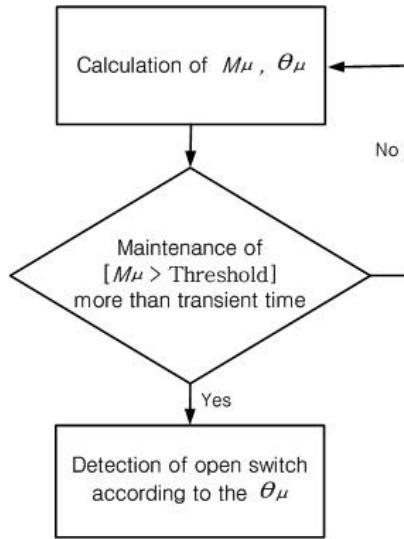
Fig. 12. Flowchart of modified Park's Vector Method.

TABLE III
DETECTION METHOD IN DC/AC INVERTER

Open Switch	d_{1_a}	d_{1_b}	d_{1_c}	d_{2_a}	d_{2_b}	d_{2_c}
S_a	0	1	1	1	0	0
$\overline{S_a}$	1	0	1	0	1	0
S_b	1	1	0	0	0	1
$\overline{S_b}$	1	0	0	1	0	0
S_c	0	1	0	0	1	0
$\overline{S_c}$	0	0	1	0	0	1

(3). The first order DFT coefficients of the phase currents are calculated by (4) and (5) to obtain independent values from the load. As shown in (6), dividing the direct component μ by the calculated DFT coefficient provides the diagnostic variable γ.

$$a_{1\_x} = \frac{2}{N}\sum_{k=1}^{N} i_x(k\tau)\cos\left(\frac{2\pi k}{N}\right) \qquad (4)$$

$$b_{1\_x} = \frac{2}{N}\sum_{k=1}^{N} i_x(k\tau)\sin\left(\frac{2\pi k}{N}\right) \qquad (5)$$

$$\gamma_x = \frac{\mu_x}{\sqrt{(a_{1\_x})^2 + (b_{1\_x})^2}}. \qquad (6)$$

For open switch fault detection in dc/ac inverter, the γ is compared to thresholds as shown in (7) and (8). Then, the faulty switch can be identified from table III. The threshold of 0.45 is a value obtained by an estimation based on experience, as stated in [8].

$$d_{1\_x} = \begin{cases} 1 : \gamma_x > 0 \\ 0 : \gamma_x \le 0 \end{cases} \qquad (7)$$

$$d_{2\_x} = \begin{cases} 1 : |\gamma_x| > 0.45 \\ 0 : |\gamma_x| \le 0.45 \end{cases}. \qquad (8)$$

Fig. 13 shows diagnostic variable γ according to switch and load power in open switch faults of converter. If conditions
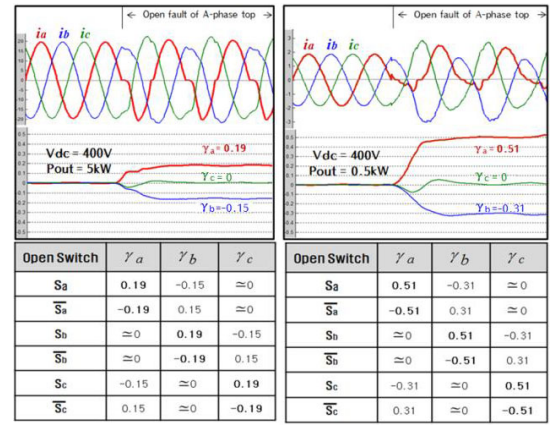
Fig. 13. γ_a, γ_b, γ_c according to load power and switch in open switch faults of converter.
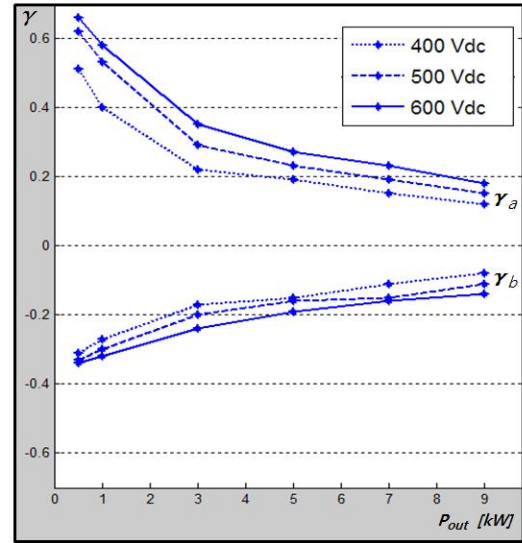
Fig. 14. g_a and g_b according to load power and DC-link voltage in open fault of S_a.

of (7) and (8) are applied in results of Fig. 13, open fault detection is possible in right side waveform but impossible in left side waveform. In the case of left side waveform, γ is lower than 0.45 even if open switch fault occurs. This is due to the presence of current through freewheeling diode as mentioned earlier.

Fig. 14 shows γ_a and γ_b according to load power and DC-link voltage in open fault of S_a. As shown in Fig. 14, if the same kind of diagnosis method for inverters is applied to converters, it is impossible to detect the open switch fault in various conditions let alone few exceptional cases. Therefore, modified fault detection method is proposed in Table IV. The faulty switch can be found by comparison of γ_a, γ_b and γ_c. The threshold of 0.05 is suitable for open fault detection of ac/dc converter given large amount of experimentations and analyses are conducted to support the data.

In this method, the transient performance is excellent due to the use of load independent variable γ. Thus, the fault detection time can be shorter than from previous method. As shown in Fig. 15, the distortion time of γ is shorter than half cycle in transient state by change of DC-link voltage. Therefore, the algorithm considering transient state can be represented in the

TABLE IV
PROPOSED FAULT DETECTION METHOD FOR AC/DC CONVERTER

Open Switch	Comparison of γ_{abc}	
Sa	$\gamma_a >$ threshold	$\|\gamma_a\| > \|\gamma_b\|$ and $\|\gamma_a\| > \|\gamma_c\|$
$\overline{Sa}$	$\gamma_a < -$ threshold	
Sb	$\gamma_b >$ threshold	$\|\gamma_b\| > \|\gamma_c\|$ and $\|\gamma_b\| > \|\gamma_a\|$
$\overline{Sb}$	$\gamma_b < -$ threshold	
Sc	$\gamma_c >$ threshold	$\|\gamma_c\| > \|\gamma_a\|$ and $\|\gamma_c\| > \|\gamma_b\|$
$\overline{Sc}$	$\gamma_c < -$ threshold	
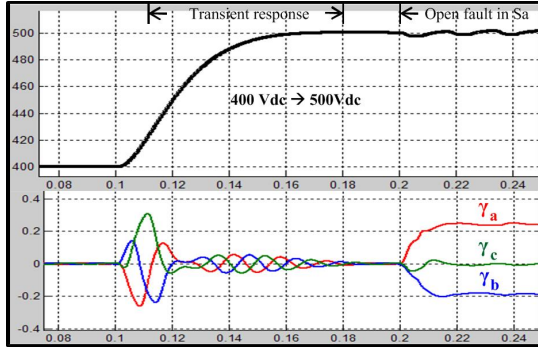
Fig. 15. Transient state and fault detection in modified Normalized DC Current Method.

flowchart of Fig. 16.

Fig. 16. Flowchart of modified Normalized DC Current Method.

Fig. 17. Experimental setup.

IV. MEASUREMENT RESULTS

The experimental setup and overall block diagram are shown in Fig. 17 and Fig. 18, respectivley. 10[kW] 3-phase back to back converter with 5[mH] reactor and 10[kW] load bank are used as shown in Fig. 17. The converter is controlled by PI control, which uses SVPWM to regulate the DC-link voltage as shown in Fig. 18. There is a generation circuit for open switch fault. Two methods are briefly summarized in the bottom two block diagrams of Fig. 18, respectively.

A. Experimental Results of Modified Park's Vector Method for AC/DC Converter

Fig. 19 shows experimental results of μ and dq-current trajectories in open switch fault. The test is performed in the 400[V] DC-link and 1[kW] load. Magnitude of μ is about 1 and arguments of μ are different from one another according to the open fault switch. It follows that Fig. 19 shows similar outcome as simulation results of Fig. 8.

Fig. 20 shows faulty phase current and trajectory of μ in six faulty cases using modified Park's Vector Method. μ moves from the origin to outer region when open switch faults occur. The threshold value of 0.5 is used in this experiment. If μ is bigger than the threshold value, the faulty switch is detected by the argument of μ from Table II once latent time of 60[ms] has elapsed. In this modified Park's Vector Method, latent time of 60[ms] is needed due to the false detection of transient state as illustrated in Fig. 21 like a simulation result of Fig. 11.
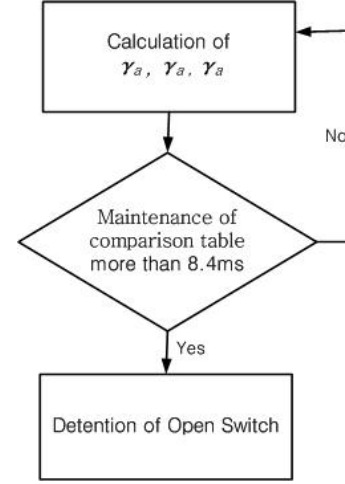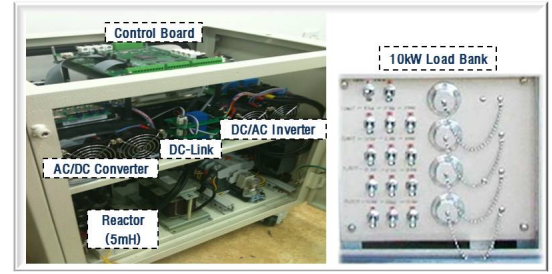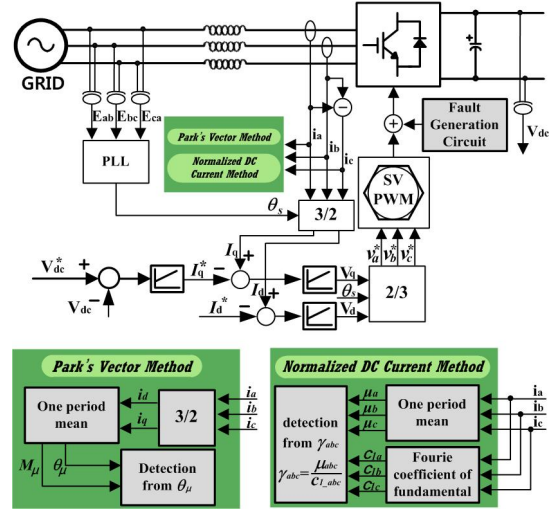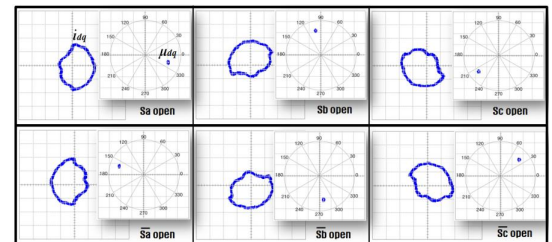

Fig. 18. Overall block diagram.

Fig. 19. Experimental results of μ and dq-current trajectories under open fault condition of ac/dc converter.
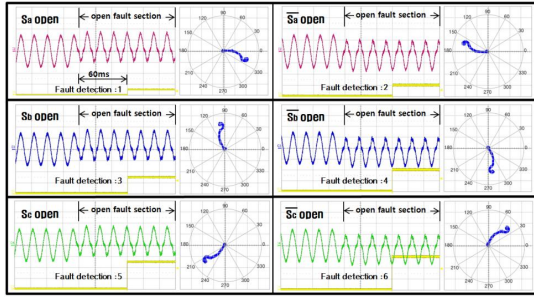
Fig. 20. Diagnosis of open switch fault using modified Park's Vector Method for ac/dc converter.
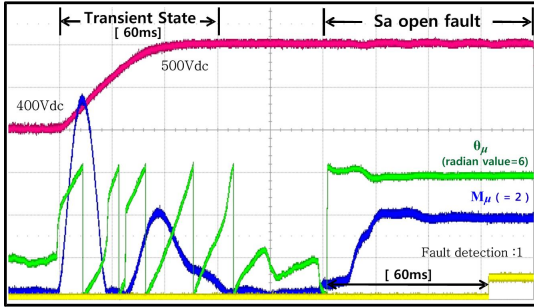

Fig. 21. Transient state and fault detection in modified Park's Vector Method.
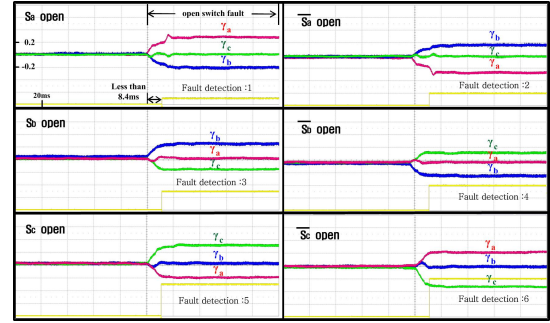

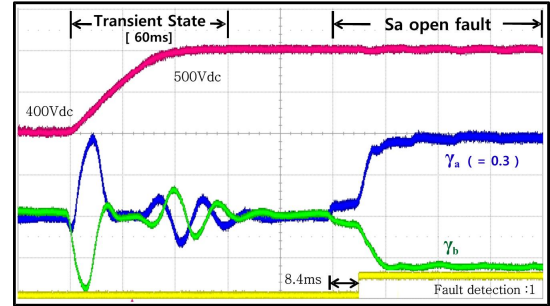Fig. 22. Diagnosis of each open switch fault using modified Normalized StateDC current method for converter.

Fig. 23. Transient state and fault detection in modified Normalized DC Current Method.

Fig. 20 shows faulty phase current and trajectory of μ in six faulty cases using modified Park's Vector Method. μ moves from the origin to outer region when open switch faults occur. The threshold value of 0.5 is used in this experiment. If μ is bigger than the threshold value, the faulty switch is detected by the argument of μ from Table II once latent time of 60[ms] has elapsed. In this modified Park's Vector Method, latent time of 60[ms] is needed due to the false detection of transient state as illustrated in Fig. 21 like a simulation result of Fig. 11.

B. Experimental Results of Modified Normalized StateDC Current Method for AC/DC Converter

Fig. 22 shows experimental results of fault detection using modified Normalized DC Current Method. The test is performed under the conditions with DC-link voltage of 400[V] and load power of 2.5[kW]. Thus, γ values of faulty phase are nearly 0.28 or -0.28 from Fig. 14 as shown in Fig. 22. Threshold of 0.05 and latent time of 8.4[ms] are used from aforementioned explanations. All detection results of six cases are shown in each fault detection signal. Fig. 23 shows transient state and fault detection like a simulation result of Fig. 15. During 60[ms] of transient state, the distortion of γ is small due to the load independent property of the method. Therefore, latent time of 8.4[ms] which defines half cycle of fundamental frequency is enough for the open fault detection. Under the conditions with DC-link voltage of 500[V] and load power of 3[kW], the γ value of faulty a-phase is about 0.3 as shown in Fig. 23. It can be confirmed through Fig. 14.

C. comparison of the modified methods

Park's Vector Method has the drawback of slower detection time than Normalized DC Current Method, because the latent time is longer. The detection time of Park's Vector Method

depends on load characteristic of transient state. If the latent time is too short, it can generate the false detection signal. However, in Normalized DC Current Method, the latent time is only half cycle of fundamental frequency because the γ vibrates with fundamental frequency in transient state.

Park's Vector Method has a drawback in low load power. If the load is low, magnitude of μ is too small. Thus, the threshold should be lower for the fault detection. As a result, the probability of false detections increases due to low threshold. On the other hand, Normalized DC Current Method is good in low load because γ is normalized by currents. However, Normalized DC Current Method has a drawback in high load power. As shown in Fig. 14, the higher load power, the lower γ becomes. Also two absolute γ becomes closer to each other with high load. Hence, the fault detection becomes ambiguous. Table V shows comparison of two modified methods.

V. CONCLUSIONS

This paper analyzed differences of open switch fault between dc/ac inverter and ac/dc converter and proposed alternative fault detection methods for IGBT open switch fault

TABLE V
COMPARISON OF TWO MODIFIED DIAGNOSIS METHODS IN AC/DC CONVERTER

Methods		Park's Vector Method for Converter	Normalized DC Current method for Converter
Detection Time		>60ms	> 8.4ms (half cycle)
Load	High	GOOD	ambiguous
	Medium	GOOD	GOOD
	Low	ambiguous	GOOD

in 3-phase ac/dc PWM converter by modifying established two fault diagnostic methods for dc/ac inverters. The analyzed results verified the validity of modified algorithms through the various experiments and simulations.

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