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RESEARCH NOTE

A New Technique for Online Open Switch Fault Detection and Location in Single-phase Pulse Width Modulation Rectifier

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ABSTRACT

Open switch fault detection in the single-phase pulse width modulation (PWM) rectifier using line current analysis technique is very applicable, but no-fault detection at high switching frequency is the main drawback of this technique. In this paper, a new online diagnosis technique for detection and location of open switch fault in the single-phase PWM rectifier is proposed. The proposed diagnosis method is based on instantaneous input voltage of the rectifier analysis. The proposed method can detect the fault in half of the power frequency under high switching frequency and load conditions. Simulation results showed the proposed technique can detect and locate all open switch faults at any switching frequency under different load conditions. In addition, the second-order output filter that is necessary for line current technique can be removed in the proposed technique.

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NOMENCLATURE

d_1, d_2	Fault indicators	C_d	DC-link capacitor (f)
Cf	Filter capacitance (f)	F_s	Switching frequency (Hz)
Lf	Filter inductance (H)	V_{ab}	Input voltage of rectifier (v)
V_N	Source voltage (v)	L_N	source inductance (H)
R_N	source resistance (Ω)	R_L	Load (Ω)

1. INTRODUCTION

Single and three-phase PWM rectifiers are well known and widely used in industries such as electric vehicle chargers, electric drives and micro grid applications. Switch fault is one of the main faults in PWM rectifier topology, which leads to decreasing reliability, and unsafe operation of the rectifiers. The most common failures in the power electronic switches are short-circuited, gate faults and open switch faults [1, 2]. Open switch fault is one of the most common faults, which occurred in PWM rectifiers. There are many techniques for diagnosis of the open switch fault in the power electronic converters [1, 4]. A technique based on a mixed logical dynamic model and state estimator presented by Xie and Ge [3]. This technique employed for open switch fault diagnosis in the single-phase cascade H-bridge rectifiers. A new open-switch fault detection for a neutral-point clamped rectifier discussed by Chen et al. [4]. A new calculation method based on phase-to-phase pole voltage deviations proposed for diagnosis process improvement. A combination of two techniques i.e., normalized DC current calculation and false alarm strategy, employed for open switch fault diagnosis. A new fast method presented by Ben et al. [5] using a residual generation between measured and observed current form factors (CFFs).

Gou et al. [6] carry out a mixed logical dynamic model and residual generation fault diagnosis. The hardware implementation of this method is simple, but the software implementation process is complicated.

Diagnosis of open switch fault using line current analysis in the frequency domain presented by Tian and Xinglai [7]. An online open switch fault diagnosis based on instantaneous line current analysis, proposed in Lai et al. [8]. This technique is powerful at low switching

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frequency (railway application), but misdiagnosis at high switching frequencies and load variations, are the main drawbacks of this technique. An improved fault detection based on deep belief networks (DBN) and least square support vector machine (LSSVM), investigated by Tiancheng et al. [9]. A method based on the residual changing rate for a single insulated gate bipolar transistor in the single-phase PWM converter presented by Dong et al. [10]. The fault detection technique was directly implemented by Huangan [11] via analyzing the mismatch signal between the applied switching states and the estimated one. An improved diagnosis system for open-circuit faults of a three-phase PWM rectifier based on line current analysis presented by Shi et al. [12]. The diagnosis module employs a hysteresis comparator to analyze the changing trend of the currents and thereby diagnoses the single open-circuit (OC) faults. Open-switch fault diagnosis and tolerant control methods for a Vienna-rectifier using bidirectional switches presented by Seok and Lee [13]. These articles have a common problem in open switch fault detection i.e., misdiagnosis at high switching frequency.

The basis of Lai et al. [8] for open switch fault diagnosis is line current analysis. The most important drawback of Lai et al. [8] work was its dependence on the output filter and the switching frequency value in the open switch fault detection. Misdiagnosis at high switching frequency was the main disadvantage of Lai et al. [8] work. Therefore, in the proposed method, these problems are resolved. The proposed diagnosis technique is based on voltage analysis. In other words, the proposed method indicates the open-switch fault by using analysis of the PWM rectifier input voltage without any additional devices. Detection and location of open switch fault in all switching frequencies ranges and load conditions, is the main advantage of the proposed technique.

2. DIAGNOSIS PRINCIPLE OF OPEN SWITCH FAULT

The schematic of the single-phase PWM boost rectifier illustrated in Figure 1. During normal operation of the rectifier, if one of the switches is open-circuited, the line current i_L and input voltage of the rectifier V_{ab}, will be distorted. If this distortion is not removed, the rectifier will be severely damaged. Therefore, identification of this fault is necessary. One of the usual technique to detect this fault is line current monitoring. Using an analyzing of the line current, open switch fault could detected. A method based on line current monitoring for diagnosis of open switch fault was proposed by Lai et al. [8]. The main disadvantages of that are:

1. No-fault diagnosis at high switching frequency
2. No-fault diagnosis under different load conditions

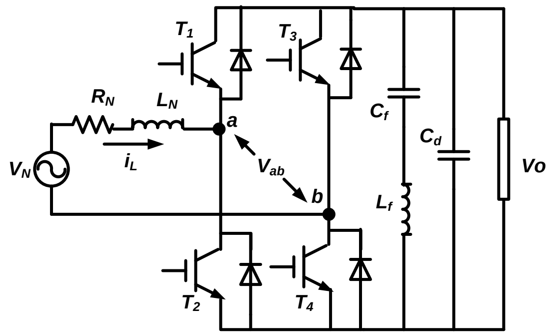


Figure 1. Topology of single phase PWM boost rectifier

To overcome these problems, in this paper, a new online technique for detection and location of open switch fault in all ranges of the switching frequency presented.

In the proposed technique, instantaneous input voltage of the rectifier "V_{ab} "has been selected as a fault indicator. The waveforms of the switches states (S1, S2, S3, S4) and V_{ab} pre and post-fault in T_1 illustrated in Figure 2. According to Figure 2, it is clear that the negative half cycle of V_{ab} during post-fault is distorted. This distortion will create in the positive half cycle, if an open switch fault takes placed for T_2 or T_3. During post-fault, the minimum/maximum values of V_{ab} waveform based on the defective switch number, are changed in any switching cycle. Therefore, detection of the open switch fault could be carried out by a minimum/ maximum points tracking process of V_{ab} waveform at any switching cycles.

3. PROPOSED DIAGNOSIS TECHNIQUE

Detection and location of open switch fault in proposed technique is done by a particular sampling process of V_{ab} waveform. The specific sampling process is accomplished by two sequence signals (Ps1, Ps2). These signals produced by a comparison of the PWM carrier signal with two references sine wave signals (with 180-

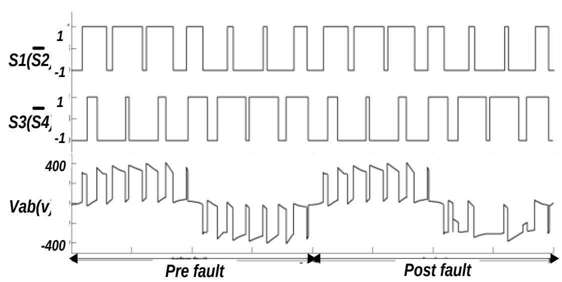


Figure 2. Vab waveform and switching states (S1, S2, S3, S4) pre and post-fault

degree phase shift with respect to each other) which was used by Lai et al. [8]. The block diagram of the proposed fault diagnosis process shown in Figure 3.

According to Figure 3, V_{ab} are sampled by two sequences pulses Ps1 and Ps2 which are called f_{s1}, f_{s2}. The sampled signals f_{s1}, f_{s2} are passed through the two filters (Low Pass Filter (LPS) and Band Pass Filter (BPF)) for extracting the fundamental component of V_{ab}. In the next step, the filter outputs are divided by the average value of the V_{ab} for insensitive to the grid voltage variation which are called d1, d2 as the fault indicators. For example, the proposed fault indicators (d1, d2) and input voltage of the rectifier waveform V_{ab} for 350 Hz switching frequency illustrated in Figure 4.

The open switch fault happened in T1 at time 0.35 s. According to Figure 4, it is clear the diagnosis signals d_1, d_2 in pre-fault, are very close together, but during faulty conditions (t>0.35 s) they separate from each other in less than half of the fundamental cycle. Consequently, the online detection of the fault is done by analysis of the d_1, d_2 waveforms, based on Figure 4 and several simulation results at different switching frequencies and load variations, the proposed conditions for open switch fault detection and location are listed in Table 1.

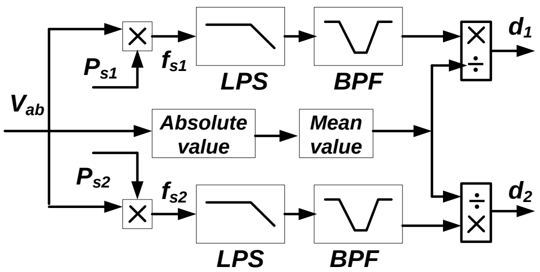


Figure 3. Block diagram of the proposed technique

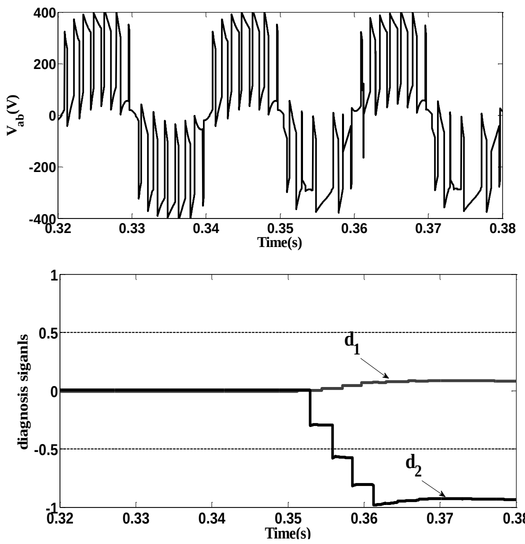


Figure 4. V_{ab} and diagnosis signals for T_1 switch fault

TABLE 1. The proposed conditions for open switch fault diagnosis

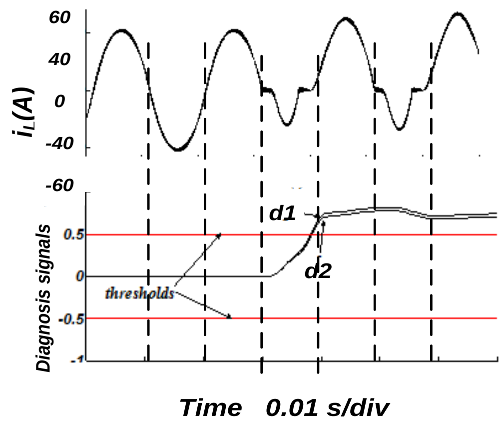
d_1	d_2	Faulty switch
$\|d_1\| < 0.5$	$d_2 < -0.5$	T_1
$d_1 > 0.5$	$\|d_2\| < 0.5$	T_2
$\|d_1\| < 0.5$	$d_2 > 0.5$	T_3
$d_1 < -0.5$	$\|d_2\| < 0.5$	T_4

For example, if $d_1 > 0.5$ and $|d_2| < 0.5$ the switch T_2 is open- circuited. In addition, in the proposed technique, the second order output filter (Cf, Lf) could be removed, but in the line current technique it is necessary.

4. SIMULATION RESULTS

In order to performance analysis of the proposed technique in online diagnosis of the open switch fault, a typical case study considered (Figure 1). The circuit parameters are: input voltage, V_N = 220V, source resistance, R_N = 0.05 Ω; source inductance L_N = 1.2 mH; DC output reference voltage V_{ref} = 300 V; DC-link capacitance, C_d = 3 mF; filter capacitance C_f=4.56mF, filter inductance L_f=0.603 mH and load R_L=15 Ω. The line current analysis and proposed technique are applied to the case study. The PWM rectifier operates under nominal load with 10kHz switching frequency. The line current waveform and its fault indicators based on literature [8] for open switch fault are shown in Figure 5. The input voltage of the rectifier and its fault indicators (proposed technique) are illustrated in Figure 6.

According to Figure 5, the line current analysis could not detect any open switch faults in T_1, T_2,T_3 and T_4 because separating of the fault indicators (based on



(a)

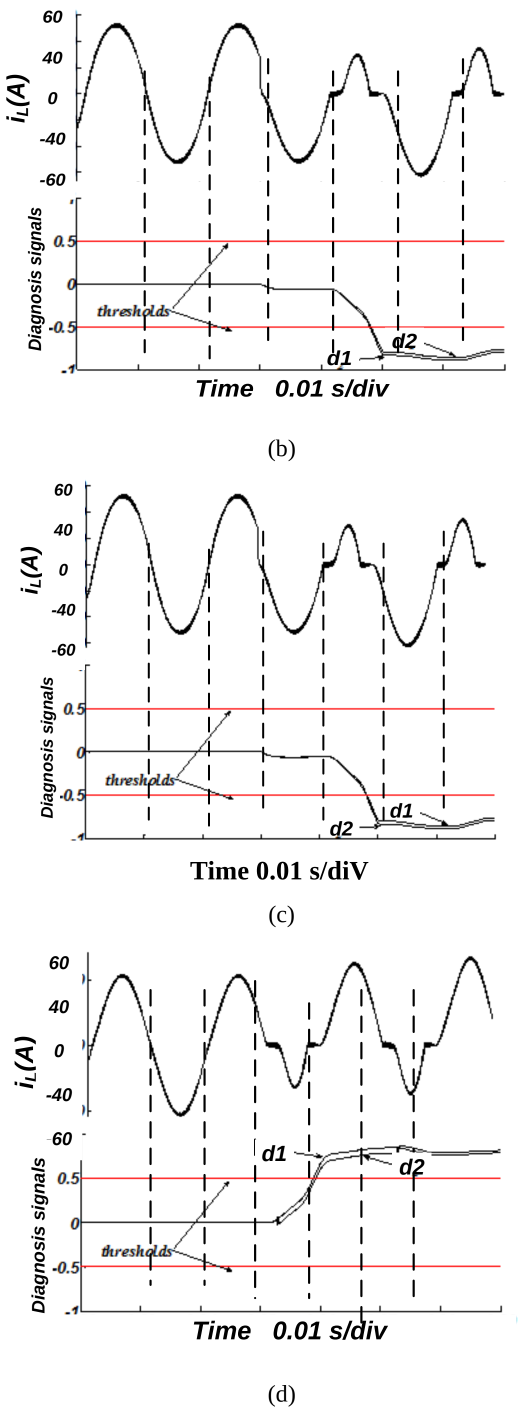
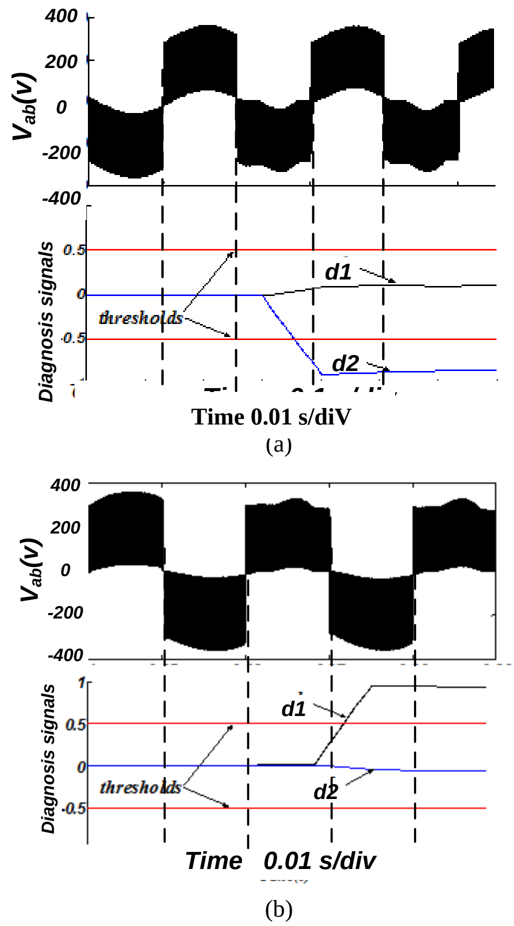
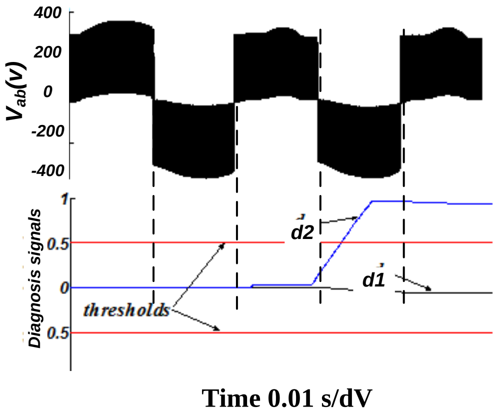


Figure 5. Simulation results based on [8] (a) iL, d1,d2 pre and post open switch fault in T1 (b) iL d1,d2 pre and post open switch fault in T2 (c) iL d1,d2 pre and post open switch fault in T3 (d) iL d1,d2 pre and post open switch fault in T4

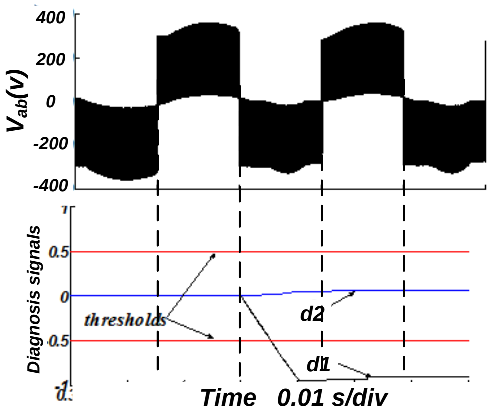
literature [8]) is complicated and almost impossible. In the proposed technique, (Figure 6), the difference between the fault indicators in the post-fault time (for all faulty switches) is significant enough for detecting the fault simply. Therefore, all of the switch faults can be easily detected and located by the proposed technique. In Figures 5 and 6 each x-axis segmentation is 0.01 second. In other words, the distance between the vertical dashed lines is 0.01 second. The detection time in the proposed technique in all of the faulty switches, is less than half of the grid voltage cycle that is the best time for online fault identification and fault location. Existence of LC filter for Lai et al. [8] is necessary, but in the proposed technique, because of the suitable difference between the fault indicators in all ranges of the switching frequencies, it could be removed. The diagnosis signals values d_1, d_2 in Figure 5 are very close together therefore, detection of fault is not possible practically. Consequently, the line current technique could not detect any open switch fault at high switching frequencies.

Figure 6 indicates the difference between diagnosis signals d_1, d_2 is significant to easily detect the fault at high switching frequencies. In other words, the proposed fault detection and location technique is independent of the switching frequency value. Therefore, the proposed method can be detected and located open switch fault at any switching frequencies easily which is significant of this paper. The summary of three recent techniques (line





(c)



(d)

Figure 6. Simulation results of proposed technique (a) Vab , d1, d2 pre and post open switch fault in T1 (b) Vab , d1,d2 pre and post open switch fault in T2 (c) Vab, d1,d2 pre and post open switch fault in T3 **(d)** Vab ,d1,d2 pre and post open switch fault in T4

current [8], AC current residual [10] and proposed technique) results at different switching frequencies and load conditions, listed in Table 2. The load range varied from 50% to 120% of the full load. Switching frequency is changed from 0.35kHz to 10 kHz. Based on Table 2 results, it is clear that the proposed technique could detect and locate all of the open switch faults at any switching frequencies and different load conditions, but the line current technique could not detect any fault at high switching frequency (>1kHz) and load conditions.

Another problem of the line current technique based on Table 2 results, is no-fault detection at light loads (<=50% of full load). Because, the line current fluctuations at light loads in the PWM rectifier, is very high therefore, sometimes fault indicators values are out of Table 1 range and sometimes they are in range. Consequently, it cannot detect the faults, but in the proposed technique, this problem has been fixed

TABLE 2. Comparison of line current and proposed technique

Switching frequency (kHz)	Load (% nominal)	line current method [8]	AC current residual [10]	Proposed technique
	50	No detect	Detect and locate	
0.35	100	Detect and locate	Detect and locate	detect and locate
	120	detect and locate	detect and locate	
	50	No detect		
1	100	detect and locate	Detect and locate	detect and locate
	120	detect and locate		
	50			
2	100	No detect	No detect	detect and locate
	120			
	50			
5	100	No detect	No detect	detect and locate
	120			
	50			
10	100	No detect	No detect	detect and locate
	120			

completely. The technique of Dong et al. [10] could detect and locate open switch fault at switching frequency lower than 2 kHz but at higher switching frequency i.e. >2kHz, it could not detect any faults.

5. CONCLUSION

In this paper, a new online technique for open switch fault diagnosis in the single-phase PWM rectifier is proposed. A technique that is based on the instantaneous input voltage of the rectifier analysis can detect and locate any open switch fault in all switching frequencies and different load conditions. Other techniques such as line current analysis and AC current residual technique, cannot detect open switch fault at high switching frequencies. The line current technique cannot diagnosis the open switch fault at light load but the proposed technique, detect and locate open switch fault at light loads. A particular sampling process of the PWM rectifier input voltage detect the open switch fault in the proposed technique. Simulation results demonstrate the powerful of the proposed technique for faulty switch identification at any switching frequencies and load conditions related to other techniques effectively.

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Persian Abstract

چکیده

تشخیص خطای کلید باز در یکسو کننده مدولاسیون عرض پالس (PWM) تک فاز با استفاده از تکنیک پایش جریان خط بسیار کاربردی است. اما عدم تشخیص عیب در فرکانس سوئیچینگ بالا نقطه ضعف اصلی این تکنیک است. در این مقاله یک تکنیک تشخیص برخط جدید برای تشخیص و مکان یابی عیب کلید باز در یکسو کننده تک فاز پیشنهاد شده است. روش تشخیص پیشنهادی مبتنی بر پایش لحظه ایی ولتاژ ورودی یکسو کننده به عنوان نشانگر خطا است. تجزیه و تحلیل این سیگنال با فرآیند نمونه برداری ویژه انجام می شود. اگر فرکانس سوئیچینگ یا تغییر بار تغییر کند، تکنیک پیشنهادی می‌تواند خطا را در نیمی از فرکانس منبع تشخیص دهد. نتایج شبیه‌سازی نشان می‌دهد که روش پیشنهادی در تشخیص و مکان‌یابی خطای کلید باز در هر فرکانس سوئیچینگ با تغییرات بار در مقایسه با تحلیل جریان خط برتری دارد. علاوه بر این در تکنیک پیشنهادی فیلتر خروجی مرتبه دوم می تواند حذف شود.