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A Simple-to-Implement Fault Diagnosis Method for Open Switch Fault in Wind System PMSG Drives without Threshold Setting

Tan Yanghong ¹, Zhang Haixia ^{1,*} and Zhou Ye ²¹ College of electrical and information engineering, Hunan University, Changsha 410082, China; tanyho@hnu.edu.cn² NARI Group Corporation/State Grid Electric Power Research Institute, Nanjing 210003, China; zhoye3@sgepri.sgcc.com.cn

* Correspondence: haixia521119@163.com; Tel.: +86-188-5102-0957

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Abstract: The conversion system is a major contributor to failure rates. These faults lead to time and cost consuming. Fault diagnosis capabilities pay as a solver to achieve a steady system. This paper presents a full analysis of permanent magnet synchronous generator wind system (PMSGWS) and proposes a special RMS voltage-based fault diagnosis method. The full analysis presents a comprehensive knowledge of faulty behaviors especially under arm current flowing or cutting off. Due to enough knowledge of faulty behaviors, the implementation of the detection method without threshold setting is contributed by the special RMS voltage. Its sample period is set longer than the time of the maximum pulse width ratio (MPR) and shorter than the fault show time of lower tube voltage. Due to this, the detection speed and robustness are achieved. By these simple settings for the fault diagnosis method, the faulty switch is detected in less than 1/4 of the period. Simulation and experimental results confirm the validity and feasibility of the new proposed fault detection method.

Keywords: permanent magnet synchronous generator (PMSG); fault diagnosis; faulty operation analysis; pulse-width modulation (PWM); current analysis; RMS; diagnosis of synchronous machines

1. Introduction

Due to high efficiency and wide flux-weakening capability, a permanent magnet synchronous generator (PMSG) has been widely employed in many industrial applications such as a wind energy system (WS). These applications have always demanded service continuity, reliability, and availability. In practice, although PMSG as one of the mature technologies in WS has been widely adopted, its accidents due to some factors such as friction [1,2], high temperature [3], and an operation process, have inevitably occurred [4,5]. Various faults may have occurred in rotor bar [6,7], engine [8], bearing [9,10], wind turbine gearboxes [11], and more. Faulty events may have damaged electrical energy, threatened the safety of the power system, and even harmed human lives and environments [4].

Currently, the diagnostic technique topic is very large [12,13]. In view of the fault parts, various approaches have been proposed to monitor and detect many kinds of faults. For instance, the methods in References [1,2] have been proposed for detecting the faults in the brake system. In Reference [6], motor current signals analysis by the tooth-fast fourier transform (FFT) has been used to detect both incipient and consolidated broken rotor bars conditions. In addition, for the detection of the half broken rotor bar fault, the other method known as the motor square current MUSIC analysis has been presented in Reference [7]. The manuscript [8] has focused on wall conveyor engines diagnosis. On the basis of these three models (signal correlation, extreme vibration, and RMS intensity), monitoring RMS and extreme values has served as a leading indicator for early detection of faults [9]. Bearing faults has

been diagnosed by the extended park vector approach [11]. The open-circuit fault (OCF) causes that the phase winding has been disconnected from or one leg of the inverter bridge has failed have been researched in Reference [14].

The fact that electronics faults in WS has accounted to about 1% of the total cost only, which was indicated in Reference [4]. Power converter failures have been generally categorized into two types of faulty, short-circuit faults (SCF) together with OCF. When an SCF has occurred, drive systems have been immediately stopped or transformed into OCF by the emergency control schedule for alleviating or isolating the fatal damage by SCF. While OCFs are associated with slow responses and less danger, it is still connected with gird for the economy and safety [15]. Yet, the potential safety problems could not have been ignored by the public [4]. Many articles have focused on reliability issues of power electronics monitoring methods [4,5,16]. Generally, these fault diagnosis methods are achieved by the output current or voltage signals such as current-based methods or voltage-based methods [17].

Current-based methods often have depended on arm current. In order to simplify the application and improve diagnostic speed, the normalized way using three-phase currents has been developed for multiple OCF in insulated gate bipolar transistors (IGBTs) for the power inverter in electric vehicles [18]. By the measurement of the output inverter currents, a fuzzy technique has detected intermittent loss of firing pulses in the inverter power switches to diagnosis [19]. The manuscript [20] has presented an OCF diagnostic method of inverters in closed-loop controlled PMSG drive systems based on the current residual vector (CRV). For detection and discrimination of OCF in a five-leg voltage source inverter feeding a five-phase biharmonic PMSG, the investigation into real-time faults diagnosis has been conducted [21]. The method by using adaptive thresholds has been proposed for multiple IGBTs OCF and current sensor faults detection [22]. The method proposed in Reference [23] was achieved by analyzing and combining the information provided with the line current shapes in the $\alpha - \beta$ frame and their normalized mean values under both healthy and faulty operating conditions. These methods have had a major drawback, which involves sensitivity to transients. The current signals have been load dependent [24]. For instance, literature [25] has indicated that current measurement noises and inverter dead-time harmonics have resulted in the distortion on DQ currents, which limits fault detection performance [26].

Aiming to dissolve this drawback, the data-driven methods have been used to detect faults. For instance, the Bayesian network in Reference [24] has been adopted for diagnosis. On the basis of FFT, the relative principle component analysis (RPCA) and the support vector machine (SVM), which is a fault diagnosis method, has been proposed for detecting OCFs in an H-bridge multilevel inverter [27]. By analyzing the output currents of normal and fault states, a fault diagnosis algorithm has been designed and achieved by a multistate data processing (MSDP) block, a subsection fluctuation analysis (SSFA) block, and the artificial neural network (ANN) block [28]. The paper [29] attempted to develop a novel method of training the ANN for a fault diagnosis technique of the OCF in converters of the PMSGWS. However, these data-driven methods take a long time to record data and to train the network [30].

Voltage-based methods have decreased sensitivity to transients and are achieved with a shorter detection time in comparison with that of current-based methods [25] even though additional sensors or other hardware devices have been required. On the basis of the output line-to-line voltage model, a novel diagnostic technique developed and proposed in Reference [31] has allowed a fast detection time and a good performance. A voltage-based detection method realized by the principle component analysis and the multiclass relevance vector machine (PCA-m RVM) has designed for the cascaded H-bridge multilevel inverter system (CHMLIS) [32]. On the aim of avoiding additional sensors, the three-phase voltages calculated by the DC link voltage and switching times contributed toward detection in Reference [25]. The calculated amount increased and was very time-consuming. Observer-based approaches have also been addressed in References [33–35]. In Reference [34], both IGBTs OCF and current sensor faults in three-phase PMSG drives have been distinguished.

The proposed diagnosis method in Reference [35] has been successful in the detection of multiple OCF. However, an adaptive threshold has been necessary for these observer-based approaches.

In practice, each switch is composed of a power switch and a parallel freewheel diode (PFD). The power switch is more sensitive than the PFD. References [15,16] have indicated the fact that an OCF may have occurred in the power switch only [15,16]. This kind of OCF is named the open switch fault (OSF). The OSFs have remained undetected and led to potential secondary faults [17,30]. After an OSF occurred in a back-to-back converter using NPC topology for wind turbine systems [36] or a three-phase pulse-width modulating (PWM) voltage source rectifier (VSR) system [37], these converters have been open to a two-way traffic for faulty current. In addition, it has two different characteristics during the zero-crossing and non-zero-crossing section. In fact, this phenomenon also has produced in the event of OSF in PMSG drives, which we verify in the next sections. If the faulty currents have gone through the converter unidirectionally, the faulty characteristics of current, harmonic, temperature distribution and more have been shown clearly [38]. However, to a bi-directional faulty current, the distortions have been found difficult due to the small residuals [37]. The performance of the method achieved by residuals may have been reduced [39]. Therefore, for distinguishing between the OSF and the normal commutation operation, the threshold has been necessary, according to Reference [37]. The dissatisfaction with reliability issues of power electronic voltage-based monitoring methods has been exposed [5].

This paper analyzes the faulty behaviors of PMSG drives in WS and proposes a new OSF detection and faulty switch identification algorithm. This proposed fault diagnosis scheme is implemented on the basis of the faulty behavior analysis. In consideration of fault-mode behavior during the zero-crossing and non-zero-crossing faulty current section, the detection method without a threshold setting comes from the feature of lower tube voltage. Due to the criteria in a lower tube voltage, a special RMS voltage is obtained in a certain period. The detection time and the robustness are also achieved by this certain period. All authors of this paper are devoted to the simple implementation of the detection method. Section 1 investigates OSF in PMSG drives of WS. The effects on current and voltage are also discussed in this section by presenting the detail fault-mode behavior. In Section 2, the identification method for OSF is proposed. The simulation and experimental results are presented in order to evaluate the fault diagnosis performance in Section 3. Lastly, the concluding remarks are provided in Section 4.

2. Investigation into Faults of PMSG Drives

The PMSGWS consists of three main parts: wind turbine (WT), PMSG, and the conversion system. The grid side converter (GSC), the motor side converter (MSC), and the DC-Link capacitor compose the wind conversion chain. It joints PMSG and the grid, isolates PMSG from the grid, reduces the damage from the PMSG, and keeps the power balance.

2.1. Faulty Circuit Analysis of the PMSG Drives

Certain simplifying assumptions are made at first. The switches of the converter are ideal whose power loss and resistance are equal to 0. The back trapezoidal EMFs (back electromotive force) of generator e_{ks} ($k = a, b, c$), phase stator resistance R_{ks} ($k = a, b, c$), and phase stator inductance L_{ks} ($k = a, b, c$) are connected in series at each phase to arrive at the PMSG drives model. Each converter consists of three arms. Each switch is composed of a power switch and a PFD. Figure 1 gives an equivalent circuit of PMSG drives, which is constrained by e_{ks} and the arm current i_k^s ($k = a, b, c$) seen in Equation (1).

$$\begin{cases} e_{as} + e_{bs} + e_{cs} = 0 \\ i_a^s + i_b^s + i_c^s = 0 \end{cases} \quad (1)$$

Figure 1. Equivalent circuit of PMSG drives.

With reference to Figure 1, the dynamics of PMSG connected to inverters is governed by the following nonlinear differential equations.

$$\begin{cases} L_{as} di_a^s / dt + R_{as} i_a^s = u_{a0} - e_{as} \\ L_{bs} di_b^s / dt + R_{bs} i_b^s = u_{b0} - e_{bs} \\ L_{cs} di_c^s / dt + R_{cs} i_c^s = u_{c0} - e_{cs} \end{cases} \quad (2)$$

Let switching function decide by s_a, s_b , and s_c . For example, $s_a = 1 \Rightarrow T_1 = ON$, $s_a = 0 \Rightarrow T_4 = ON$. Arm currents i_k^s flowing into the windings are defined as positive. Current direction and switching signal determine the lower tube voltages u_{kN} ($k = a, b, c$) that can be expressed by the equation below.

$$u_{kN} = s_k u_{dc} \quad (k = a, b, c) \quad (3)$$

where u_{dc} is the dc-link voltage. u_{kN} plus the N-to-neutral voltage u_{N0} is the winding-to-neutral voltages u_{k0} ($k = a, b, c$). Adding three sub-equations of Equation (2), we can obtain the mathematic expressions of u_{N0} and u_{k0} .

$$u_{N0} = -(s_a + s_b + s_c) u_{dc} / 3 \quad (4)$$

$$\begin{cases} u_{a0} = (2s_a - s_b - s_c) u_{dc} / 3 \\ u_{b0} = (2s_b - s_a - s_c) u_{dc} / 3 \\ u_{c0} = (2s_c - s_b - s_a) u_{dc} / 3 \end{cases} \quad (5)$$

If the power switch fault by the gate driver failure results in OCF in MSC, the PFD of the faulty power switch still connects with MSC, builds the current path, and contributes to PMSG current flowing. Assuming that T1 fails to turn on or off, we only control T4. For the sake of the zero-crossing condition of the faulty current, the analysis of faulty behaviors is divided into the two following parts.

2.1.1. (A) The Non-Zero-Crossing Section of the Faulty Current ($i_a^s \neq 0$)

In detail, if $s_a = 0$, the lower switch T4 is on u_{aN} is identically equal to zero. When $s_a = 1$, u_{aN} and i_a^s are found based on the following rules. e_{bs} and u_{dc} affect the conduction of the antiparallel diode VD4. Once forward conduction current flows through VD4, $u_{aN} = 0$ and $i_a^s > 0$. If not, i_a^s flows from the generator and charges the DC-Link capacitor $u_{aN} = u_{dc}$ and $i_a^s < 0$. In other words, if u_{aN} is proper, i_a^s can flow through VD1 or VD4. So i_b^s can flow though bilaterally. Now, the T1 fault results in the following relation.

$$\begin{cases} u_{aN} = 0 & i_a^s > 0 \\ u_{aN} = u_{dc} & i_a^s < 0 \end{cases} \text{ and } s_a = 1 \quad (6)$$

Substituting Equation (6) into Equation (2), we get the phase-A equations below.

$$\begin{cases} L_{as} di_a^s / dt + R_{as} i_a^s = u_{N0} - e_{as} & i_a^s > 0 \\ L_{as} di_a^s / dt + R_{as} i_b^s = (s_a u_{dc} + u_{N0}) - e_{bs} & i_a^s < 0 \end{cases} \quad (7)$$

As is clear from Equation (7), the arm current can flow through bilaterally. The form of Equation (7) indicates that the distortions of arm current are nonlinear.

2.1.2. (B) The Zero-Crossing Section of Faulty Current ($i_a^s = 0$)

The threshold voltage of VD1 or VD4 is assumed as u_D . e_{as} is decided by the wind turbine. When $i_a^s = 0$, u_{a0} is equal to e_{as} in view of Figure 1. e_{as} and u_{N0} affect the conduction of the antiparallel diode VD1 or VD4. If $e_{as} - u_{N0} > u_D$, VD1 conducts. As a consequence, $u_{aN} = u_{dc} - u_D$ and $u_{N0} = e_{as} - u_{dc} - u_D$; if $u_{N0} - e_{as} < u_D$, VD4 conducts. After this, $u_{aN} = -u_D$ and $u_{N0} = e_{as} - u_D$. We also analyzed the condition where VD1 and VD4 cannot conduct. The switches on phase B and C are still controlled by s_b and s_c . According to Reference [40], three-phase voltages are constrained by the equation below.

$$u_{a0} + u_{b0} + u_{c0} = 0 \quad (8)$$

Taking $u_{a0} = e_{as}$ and changing Equation (3) into Equation (8), we can obtain the following formula.

$$u_{N0} = -[e_{as} + (s_b + s_c)u_{dc}]/2 \quad (9)$$

This time $u_{aN} = [3e_{as} + (s_b + s_c)u_{dc}]/2$, which is different from the conditions related to VD1 or VD4 conducting.

2.2. Distortion of Arm Current

2.2.1. The Control Strategy

The control strategy for MSC generally includes the following two closed loops: speed loop and flux loop [41]. The complete block diagram is shown in Figure 2.

Figure 2. The control strategy for MSC.

In view of Figure 2, we express PWM control signals u_{rk} through the equation below.

$$u_{rk} = g(i_k^s, \omega) \quad (10)$$

where ω is the actual rotor speed. In Equation (10), i_k^s takes part in flux regulation. We assume that the wind speed is fixed. Then, ω is a constant. i_k^s change when a T1 fault occurs. In fact, once an OSF happens, i_k^s should change. As a consequence, u_{ra} , u_{rb} , and u_{rc} are also altered due to Equation (10). Switching signals are confined by u_{ra} , u_{rb} , and u_{rc} , which is shown in Figure 2.

In general, the PWM control is achieved by a comparing process described in Figure 3. In this process, the reference value u_0 is always stable after leaving the factory.

Figure 3. The control strategy for PWM.

It is assumed u_{a1} is deformed into u_{a2} after T1 fault occurrence. This assumption is built on the basis of the experiments and simulations in Section 2.2.2. Comparing u_{a1} and u_{a2} with u_0 , we obtain different PWM signals as $P1$ and $P2$. Certain deductions can be made regarding that $P1$ and $P2$ are different. In an actual system, the frequency of u_0 is up to several thousand Hz. More errors between $P1$ and $P2$ would appear. Therefore, a strong coupling relationship between switching signals and arm current exists.

2.2.2. The Dynamics of Arm Current

Experiments and simulations are conducted to analyze the dynamics of the current. The experimental devices are shown in Figure 4. The main parameters of PMSG drives are given in Table 1.

Figure 4. Experiment devices: (a) control panel; (b) generator; (c) the back-to-back converter control circuit.

Table 1. System parameters of experiments.

Device	Parameters	Device	Parameters
generator	rated power	2.2 kW	DC-link capacitance
	rated voltage	0.38 kV	Grid equivalent inductance
	rated frequency	50 Hz	Rotational inertia of the generator
	resistance	0.86	
	inductance	11.3 mH	
	voltage coefficient	0.62 kv	
			1000 uF
			2 mH
			0.0032 kg·m ²

With parameters including a reference speed of 1200 r/min together with a load torque equal to 60% of the rated torque, experiments are conducted under two different conditions that are of a normal operation termed the T1 fault. T1 is the upper switch of MSC in phase A. For leading to OSF, the switching signal of T1 is forced to zero. The dynamic responses of i_k^s are shown in Figure 5a,b. All curves of i_k^s are bidirectional. Their envelopes are trigonometric functions with three similar elements. All distortions are hard to express by mathematical equations. Therefore, we believe the distortions of arm current are nonlinear.

Figure 5. Experimental results regarding the time-domain waveforms of arm currents: (a) The normal operating condition; (b) the operating conditions at the time of the T1 fault.

The model simulations of PMSG drives are carried out by using PSCAD software. The model of PMSGWS is shown in Figure 6. The main system parameters of simulations are given in Table 2. T1 and T4 are the top and lower switches in phase A, respectively. Setting wind speed at 10.5 m/s, we simulate the model. Its dynamic responses of i_k^s are plotted in Figure 7.

Figure 6. The model of PMSG drives.

Table 2. System parameters of simulations.

Device	Parameters	Device	Parameters
generator	rated power	1.58 MVA	DC-link capacitance
	rated voltage	0.69 KV	200 mF
	rated frequency	50 HZ	Grid equivalent inductance
	resistance	0.017 pu	0.2 mH
	inductance	0.064 pu	Rotational inertia of the generator
	voltage coefficient	1500 V	2 pu

Figure 7. Simulation results regarding arm currents: (a) The normal operating condition; (b) the operating condition at the time of the T1 fault; (c) The arm current residuals in the event of the T1 fault.

In Figure 7a,b, all i_k^s are bidirectional. The envelopes of curves are trigonometric functions. The two curves in Figure 7b are obtained in the event of the T1 fault. The currents distort nonlinearly. Similar characteristics are reflected by both simulations and experiments. These similar characteristics also prove the simulation model is effective and available.

For analyzing dynamics of arm current, we also obtain the arm current residuals as shown in Figure 7c. In Figure 7c, three-phases residuals are generally not equal to 0. Therefore, i_k^s are distorted most of the time. All these curves are hard to express by mathematical functions. The distortions of i_k^s are nonlinear. All results demonstrate the dynamic faulty behaviors in the event of the T1 fault. The distortions of i_k^s are nonlinear.

2.3. Distortion of Voltages

2.3.1. The Lower Tube Voltage

Taking the T1 fault as an example, we study the responses of the lower tube voltage. Table 3 gives the responses of u_{aN} during the T1 fault.

Table 3. The values of u_{aN} .

Faulty Switch	Current Direction	$(s_a s_b s_c)$							
		000	001	010	011	100	101	110	111
T1	$i_a^s > 0$	0	0	0	0	0	0	0	0
	$i_a^s < 0$	0	0	0	0				
	$i_a^s = 0$	If VD1 conducts, $u_{aN} = u_{dc} - u_D$. If VD4 conducts, $u_{aN} = -u_D$. If both VD1 and VD4 cannot conduct, $u_{aN} = [3e_{as} + (s_b + s_c)u_{dc}]/2$							
No faulty switch	both	0	0	0	0				

Let us now check all the values in Table 3. When OSF occurs in the upper switch and the arm current is positive, the lower tube voltages of faulty phase are equal to 0. In other words, the lower tube voltages are not equal to DC-link voltage anymore when the faulty arm current is positive. When $i_a^s = 0$, u_{aN} is obtained along with the various values that are unequal to 0 and u_{dc} . These criteria are a very helpful key for the OSF detection problem, which is summarized in Table 3. For the convenience of expression in the next sections, we call these periods u_{aN} , which are kept at 0 during the fault show time. The rest of the fundamental period is named the fault blank time.

2.3.2. The Winding-to-Neutral Voltage

We know u_{k0} in the normal condition as Equation (5). In this section, the mathematical expressions of u_{k0} in the event of the T1 fault are analyzed. At first, we analyze the condition regarding $i_a^s \neq 0$. Take Equation (6) into Equation (8) and calculate u_{bN} , u_{cN} by using Equation (3). Now we can obtain the formula below.

$$\begin{cases} u_{N0} = -(s_b + s_c)u_{dc}/3 & i_a^s > 0 \\ u_{N0} = -(s_a + s_b + s_c)u_{dc}/3 & i_a^s < 0 \end{cases} \quad (11)$$

Because the assumption that switches of the converter are ideal is made at the beginning of this section, we consider u_D as 0. During $i_a^s = 0$, $u_{a0} = e_{as}$. The values of u_{aN} are listed in Table 3. We can obtain the following equations.

$$\begin{cases} u_{N0} = e_{as} - u_{dc} & \text{VD1 conducts} \\ u_{N0} = e_{as} & \text{VD4 conducts} \\ u_{N0} = -[e_{as} + (s_b + s_c)u_{dc}]/2 & \text{both VD1 and VD4 cannot conduct} \end{cases} \quad (12)$$

u_{kN} plus u_{N0} is u_{k0} . In view of i_a^s , we can express u_{k0} below.

$$\begin{cases} u_{a0} = -(s_b + s_c)u_{dc}/3 & i_a^s > 0 \\ u_{a0} = (2s_a - s_b - s_c)u_{dc}/3 & i_a^s < 0 \\ u_{a0} = e_{as} & i_a^s = 0 \end{cases} \quad (13)$$

$$\begin{cases} u_{b0} = (2s_b - s_c)u_{dc}/3 & i_a^s > 0 \\ u_{b0} = (2s_b - s_a - s_c)u_{dc}/3 & i_a^s < 0 \\ u_{b0} = s_b u_{dc} + e_{as} & i_a^s = 0 \text{ and VD1 conducts} \\ u_{b0} = (s_b - 1)u_{dc} + e_{as} & \text{and VD4 conducts} \\ u_{b0} = [-e_{as} + (s_b - s_c)u_{dc}]/2 & i_a^s = 0 \text{ and both VD1 and VD4 cannot conduct} \end{cases} \quad (14)$$

$$\begin{cases} u_{c0} = (2s_c - s_b)u_{dc}/3 & i_a^s > 0 \\ u_{c0} = (2s_c - s_a - s_b)u_{dc}/3 & i_a^s < 0 \\ u_{c0} = s_c u_{dc} + e_{as} & i_a^s = 0 \text{ and } VD1 \text{ conducts} \\ u_{c0} = (s_c - 1)u_{dc} + e_{as} & i_a^s = 0 \text{ and } VD4 \text{ conducts} \\ u_{c0} = [-e_{as} + (s_c - s_b)u_{dc}] / 2 & i_a^s = 0 \text{ and both } VD1 \text{ and } VD4 \text{ cannot conduct} \end{cases} \quad (15)$$

Besides the condition of $i_a^s = 0$, u_{k0} are decided by s_k and u_{dc} . It is well known that s_k are logical variables. Therefore, u_{k0} would be discrete most of the time. u_{a0} are less than 0 during $i_a^s > 0$ according to Equation (13). As listed in Equations (13)–(15), the values of u_{k0} are affected by e_{as} , s_b , and s_c . u_{k0} get various values, for example, $-2u_{dc}/3$, 0 , $2u_{dc}/3$, $-u_{dc}/3$, $u_{dc}/3$, $u_{dc} + e_{as}$, e_{as} and so on. Owing to the randomness of wind, the values of e_{as} are in a wide range. Due to this, we can deduce that u_{k0} possibly has more than 10 values. The values of u_{k0} are more than that of u_{kN} . Therefore, the distortions of u_{kN} are easier to discover than that of u_{k0} .

Looking back at all these investigations, we can list the following conclusions. First, the bidirectional arm current can flow through MSC in the event of OSF. The relationship between arm current and the switching signal is strong coupling. The distortions of arm current are nonlinear. In addition, when an OSF occurs, the fault show time of u_{kN} comes out. The values of u_{k0} have a wide range. The distortions of u_{kN} are easier to discover than that of u_{k0} .

3. The Proposed Open-Circuit Fault Diagnosis

Too many factors are influenced on arm current in the event of an OSF in MSC. The wide range of values u_{k0} is too complex to detect. Fortunately, we find the criteria that is summarized in Table 3 as a very helpful key for the OSF detection problem. The fault diagnostic formula is studied below.

3.1. Method of Fault Diagnose

Figure 8 illustrates the proposed fault diagnosis algorithm for detecting the OSF condition and identifying the faulty switch. This algorithm contains three steps including measurement, comparison, and classification.

Figure 8. Block diagram of the fault detection method.

Measurement is the most important process of the proposed fault diagnosis algorithm. After this process, we can obtain a special RMS voltage U_{kN} , which is the key for deciding fault localization variables. In addition, the details of this process are explained in Section 2.3.

The second step is a comparison between U_{kN} and u_{dc} . Let DC-Link reference voltage U_{dcref} equal u_{dc} . By this step, fault localization variables U_k appear. If U_k is equal to 0 or 1, the fault show time would appear. It can also deduce that an OSF happens. We collect the values of U_k after all possible single switch faults occurred in MSC as Table 4 lists.

Table 4. The fault location rules for the faulty switch.

U_a	U_b	U_c	Faulty Switch	U_a	U_b	U_c	Faulty Switch
1			T4	1			T6
0			T1	0			T3
		1	T2			0	T5

Classification is designed as the last step of the detection method. Table 4 shows different faulty switches come with different fault localization variables U_k . So the faulty switch can be detected according to these variables.

In this fault diagnosis method, the setting of threshold is unnecessary. Only the values in the fault show time are considered. The misjudgment during the faulty current cutting off would should be avoided. In the detection process, we only monitor the lower tube voltage and sample with a certain period. The implementation of the detection method for OSF in MSC is very simple. The fault feature is obtained from the lower tube voltage directly in which it is easier to distinguish faulty switches in comparison to residuals. Surely, T_s influences on the detection speed and the cost of the detection method.

3.2. Fault Detection Time

PWM frequency is several hundred times bigger than grid frequency and is not proper for sampling because of the high cost of the sensors. To shorten this cost, we choose other frequencies to sample. As the above proposed method, T_s is the one we use to monitor lower tube voltage. T_s is the major parts of fault detection time. The shorter detection time, the less the period T_s . The other problem is choosing T_s , which may affect the reliability of the detection method. In detail, if T_s is too large, the fault show time may not be detected and if it is too small, the possibility of false detection increases. Therefore, this part introduces many problems such as how to choose the proper period T_s , how long the fault detection time takes, and so on.

(A) Choosing the Proper Period T_s

Several methods such as intelligent methods and empirical selection are effective and available to obtain T_s . Considering the merit and disadvantage of experimental conditions and each method, one of the most reliable choice methods known as the empirical selection is employed in this paper.

T_s is bigger than the time of the maximum pulse width ratio (MPR) and shorter than the fault show time, according to Section 2.1. The work [42] indicates the pulse width ratios are derived from the reference curve for the PWM. During the pre-delivery test, we can change the wind between cut-in and cut-out speed in different modes such as steady speed, random wind, ad step wind. Then, MPR of all wind modes can be recorded. So T_s can be chosen according to MPR.

(B) The Calculation of Fault Detection Time

If an OSF occurs, the fault show time as analyzed in Section 2.3.1 would appear. Once the fault occurs at the beginning of the fault blank time, the detection time is the longest. It has to wait more than half of the current fundamental period for the fault show time.

Let us suppose the fault occurs at t_0 . The period of the fault blank time T_x and T_s are not proportional as seen in Equation (16).

$$T_x = n * T_s + \varepsilon \quad (16)$$

where $\varepsilon < T_s$; n is a positive integer. Therefore, assuming T_c as the telecommunication and calculation time, the detection time T is equal to the longest one $T_{\max}$ as seen in Figure 9a.

$$T = T_{\max} = (n + 2)T_s + T_c \quad (17)$$

$$T = T_{\min} = T_s + T_c \quad (18)$$

Figure 9. fault detection time: (a) The maximum detection time and (b) the minimum detection time.

If the fault occurs at the beginning of the fault show time, the detection time is the shortest one $T_{\min}$. Assuming the fault occurred at t_0 , the detection time T as seen in Figure 9b shown can be expressed.

In conclusion, the values of detection time are less than one current fundamental period. In addition, the shortest detection time is nearly equal to the sampling time.

3.3. Measurement of Electrical Signal

The key of the fault diagnosis algorithm is the measurement process. Its principle is shown in Figure 10, which we also realize in the next simulation part. In this process, the special RMS voltage U_{kN} is calculated. Before the calculation of U_{kN} , the period T_s should be obtained after the pulse width measurement. The detail expatiation about T_s is listed in Section 2.2.

Figure 10. The measurement diagram of the electrical signal.

The calculation of U_{kN} is shown below.

$$U_{kN} = \sqrt{\frac{\int_{t-T_s}^t [u_{kN}(t)]^2 dt}{T_s}} \quad (19)$$

Assume T_s is proper and take T1 fault as an example. If the measurement is conducted during the positive cycle of faulty current. U_{aN} are equal to 0 due to $u_{aN} = 0$ according to Table 3. Once faulty current turns to a negative cycle, U_{kN} can be expressed by Equation (20) below.

$$U_{aN} = \sqrt{\frac{\int_{t-T_s}^t [s_a u_{dc}]^2 dt}{T_s}} \quad (20)$$

U_{aN} are unequal to 0. In addition, when faulty current is under the zero-crossing section, u_{aN} may be not equal to 0 as U_{aN} . That means only when the fault show time comes out, U_{kN} is 0.

4. Simulation and Experimental Results

The model of PMSGWS as illustrated in Figure 6 is built on the basis of the PSCAD environment. The main system parameters of PMSG for simulation are given in Tables 1 and 2. The parameters are set the same as expressed in Section 2.2.2. Figure 4 gives the photos of experiment devices. Dynamic responses of voltage are shown in this section. Figure 11 is the experimental responses of the lower tube voltage. The results of the simulations are illustrated by Figures 12 and 13.

Figure 11. Experimental results: (a) The normal operating condition; (b) the OSF from T1.

Figure 12. Simulation results regarding the time-domain waveforms of the lower tube voltage in MSC: (a) The normal operating condition; (b) the open-circuit fault from T1.

Comparing Figure 11a with Figure 11b, it is visible that, under different operating conditions, although the similar feature that all u_{aN} skip on 0 and 0.65 Kv is revealed in the fault blank time, different characteristics of u_{aN} are shown during the fault show time.

We also assume T1 and T4 are the top and lower switch of MSC in phase A, respectively. Figures 12 and 13 present the simulation results during T1 fault occurrence with an imposed reference wind speed of 10.5 m/s. The time-domain waveforms of lower tube voltage are similar to that obtained by experiments. u_{aN} change with the fault show time when OSF occurs in T1. During $i_a^s = 0$, u_{aN} shows different features in comparison with that during $i_a^s \neq 0$. Comparing Figure 12 with Figure 11, it is

visible that u_{k0} is more complex than u_{kN} . There are several values of u_{k0} . u_{a0} is smaller than 0 during $i_a^s > 0$.

Figure 13. Simulation results regarding the time-domain waveforms of the stator voltage in MSC: (a) The normal operating condition; (b) the open-circuit fault from T1.

These simulation results indicate a similar phenomenon as obtained by experiments. In details, u_{aN} does not skip on 0 and 1.5 Kv during the fault show time. u_{k0} is more complex than u_{kN} . As shown in Figure 13, u_{k0} with a high frequency are discrete most of the time. During the zero-crossing section, u_{k0} obtains some values not as the non-zero-crossing section. The responses in Figures 12 and 13 are consistent with experiments as well as analyses in Section 1.

The effectivity and availability of the simulation model are verified according to the above analysis of faulty behaviors. Considering the damage to devices, we test the diagnosis method in simulation surroundings. Six cases including the normal condition with 7 m/s, the normal condition with 10.5 m/s, OSF in T1 with 7 m/s, OSF in T4 with 7 m/s, OSF in T1 with 10.5 m/s, and OSF in T4 with 10.5 m/s are demonstrated for verifying the performance of the proposed method. All faults occur at the 0.02 s second. Setting sample time as a 0.003 s, we can obtain the values of U_a .

These values of localization variables in Figure 14 can be obviously categorized into three main types: normal case between 0 and 1, T1 fault case reducing to 0, and T4 fault case up to 1. The OSF in T4 with 7 m/s is detected in the shortest time of about 0.003 s. The longest detection time is about 0.015 s showing in the event of T1 fault with 7 m/s. These responses prove that the proposed diagnosis algorithm with a certain period can distinguish a faulty switch in different wind speeds. It also proves that the proposed diagnosis algorithm can achieve fault detection in this paper.

Figure 14. Phase-A location variables at different cases.

Moreover, we also take these results to compare with other previous methods, as presented in Table 5. The proposed method with similar detection speed as that in Reference [18] even though

the faulty current in Reference [18] is considered as a unidirectional one. Absolutely, the robust and accuracy proven by the results can meet the requirements of grid stability.

Table 5. The comparison between the proposed method and already existing method.

Diagnostic Methods	The Object	The Complex of Background	Faulty Current	Threshold Setting
Current-changing trend detection method [34]	The PWM voltage source rectifier		bilateral	need
The normalized way [18]	Power inverter in electric vehicles		unidirectional	need
The zero-crossing feature-based method [33]	back-to-back converters using the NPC topology		bilateral	need
Proposed method	MSC of PMSGWS		bilateral	unnecessary

5. Conclusions

In order to handle unforeseen faults and to achieve high reliability levels with the wind conversion chain, the fault detection and identification are becoming more and more important for industrial applications. In this paper, the analysis under arm current flowing or cutting off enhances the knowledge of faulty behaviors and works on finding the criteria to detect faulty switches. Then, a simple diagnostic method for OSF in MSC of a PMSG drive for wind turbine application is proposed. The fault diagnosis process without threshold settings is one of the main advantages of this method. Simulation and experimental results confirm the validity of the new proposed fault detection method.

The full analysis of faulty behaviors in this paper pay as a key for diagnosis, fault tolerance, and optimized control in future research. Due to the merit without thresholds, the proposed method may be extended to a wider application. In further research, we will use these obtained principles as the base. An engineering implementation is also a future goal.

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Nomenclature

e_{ks}	back trapezoidal EMFs of generator (kV)
R_{ks}	phase stator resistance (Ω)
L_{ks}	phase stator inductance (mH)
i_k^s	stator current (kA)
u_{No}	N to neutral voltage (kV)
s_k	gate command signals
u_{kN}	lower tube voltage (kV)
U_{kN}	special RMS voltage (kV)
T_x	the fault blank period (ms)
T_s	the sampling period (ms)
U_{dcref}	DC-Link reference voltage (kV)

T_c	the telecommunication and calculation time (ms)
T	detection time (ms)
ω	the actual rotor speed (rad/s)
u_{rk}	PWM control signals
U_k	fault localization variables

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