International Journal of Control and Automation
Vol. 7, No. 11 (2014), pp. 401-416
http://dx.doi.org/10.14257/ijca.2014.7.11.39

Voltage-based On-Line Fault Detection and Faulty Switch Identification under Multiple Open-Switches in Grid-Connected Wind Power Converter

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Abstract

New voltage-based on-line fault detection and faulty switch identification algorithms under multiple open-switches in a grid-connected wind power converter are proposed in this paper. The proposed algorithms are based on the three-phase voltages which are calculated by using the DC link voltage and switching times determined from the space vector PWM scheme. From the calculated three-phase voltages, the absolute of average phase voltage and normalized three-phase RMS voltages are obtained to be used for the fault detection and faulty switch identification algorithms in three-phase AC/DC PWM converter. To determine faulty switches, three-phase voltages and RMS currents are taken as faulty switch localization variables. The complete diagnosis is carried out by a simple method during operation, which does not require any additional sensors. Therefore, the proposed methods are cost-effective and easy to use. To verify the validity and performance of the proposed algorithms, the simulation is carried out using the PSIM software for twenty-one cases of faults including multiple open-switches. As a result, the proposed scheme can effectively detect the occurrence of fault as well as faulty switches for these conditions independent of operating conditions.

Keywords: *Faulty switch identification, On-line fault detection, Open-switch fault, Voltage-based approach, Wind power converter*

1. Introduction

Most of the countries in the world use coal, oil, and natural gas to supply most of their energy needs. As world population continues to grow and the limited amounts of fossil fuels begin to diminish, it may not be possible to provide the amount of energy demanded by the world by only using fossils fuels. Burning fossil fuels to convert the energy also creates air, water, and soil pollution. In addition, it produces greenhouse gases which are responsible for the global warming. There are plenty of ways to convert the energy without fossil fuels like renewable energy. Renewable energy resources such as wind, solar, and hydropower offer clean alternatives to fossil fuels.

Among them, the wind power is a cost-effective, efficient, and abundant source of electricity. For this reason, the wind industry has been growing rapidly in recent years to reduce the global warming and the dependence on fossil fuels. Wind energy conversion system (WECS) is generally composed of a wind turbine, an electric generator, a generator-side converter and a grid-side inverter. Different structures for a WECS can be realized to convert the wind energy at varying wind speeds to electric power. The most advanced generator type is the permanent magnet synchronous generator (PMSG) used for variable speed wind power generation systems.

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ISSN: 2005-4297 IJCA

Generally, power switch failures can be classified as short-switch fault and open-switch fault. Short-switch faults are produced by gate circuit degradation and AC over current. A short-switch fault generates an unbalanced over current, which causes damages in other important devices of the system. The unbalanced over voltage and over current may result in fatal accidents. Therefore, such a fault should be detected immediately to protect expensive devices. There are several reasons that cause an open-switch fault. The open-switch faults are created by the disconnection of a wire from the switching devices due to a thermal cycling or a gate driver failure. Open-switch faults may be caused by high collector current. Finally, the failure in gate driver circuits is one of the most common causes of open-switch fault. Although open-switch faults do not cause the shutdown of the entire system, the performance will be degraded. Also, the unbalanced operation caused by the open-switch faults may generate secondary problems in the system. When any power switch presents state of failure in a generator-side converter or in a grid-side inverter, the other components of the system can be damaged. For this reason, open-switch faults should be detected as soon as the fault occurs. It is very important to identify the location of faulty switch properly. If any kinds of open-switch faults occur either in a generator–side converter or in a grid-side inverter, the energy supplied to the grid will be reduced continuously.

Diagnostic methods for the open-switch fault in an AC/DC PWM converter have been developed with a special focus on condition monitoring [1]. The difference in detection methods between three-phase AC/DC PWM converter and inverter has been analyzed for IGBT open-switch faults [2]. Based on these techniques, an alternative fault detection method has been proposed for the PWM inverter. A new voltage-based approach without additional sensors has been proposed for open-switch fault diagnosis in closed loop controlled PWM voltage source converter [3]. In this scheme, the information contained in the reference voltages which are available from the controller has been used as detection variables. Four detection techniques using various voltage informations have been introduced for fault diagnosis in voltage-fed asynchronous machine drive systems [4]. Application of the fuzzy logic for a fault diagnosis of switching device in a voltage-fed induction motor was presented in [5].

A survey was done on the existing methods of fault diagnosis and protection of IGBT [6]. A real-time diagnosis for multiple open-switch faults in voltage-fed PWM motor drives was proposed in [7, 8]. Open-switch fault diagnosis of AC/DC PWM converter has become essential in wind turbine applications, not only to avoid secondary fault in the AC/DC PWM converter but also to improve the stability and reliability of entire system. A diagnostic method for multiple open-switch faults in the two converters of a PMSG drive has been proposed for wind turbine applications [9]. A diagnostic method for a doubly-fed wind power converter in microgrid system has been presented [10], which is based on the investigation of the characteristics of current signals. A system reconfiguration topology was designed for the microgrid system to keep a doubly-fed induction generator continue running after the open-switch faults. A fault diagnosis method based on the analysis of the load currents in voltage source inverters was proposed [11], which was an extension of the normalized dc components method. By combining the normalized dc components with additional diagnostic variables, the certainty of the diagnoses under transients and light loads has been markedly improved.

Since the performance and reliability of the system are degraded due to the open-switch fault, a fault tolerant control method is needed to solve this problem. A fault diagnostic method and fault tolerant topology have been proposed for the generator–side converter [12] to minimize the unbalance of AC input current and the ripple voltage in the DC-link of three-phase AC/DC PWM converter. Fault detection and isolation on a PWM inverter using the knowledge based model were investigated [13]. This scheme was based on the analysis of the current vector trajectory and instantaneous frequency in faulty mode and validated through the simulations and experiments. Some diagnostic methods use the fuzzy theory and model reference adaptive system [14]. In this study, the simulations and experiments were carried out for a digitally controlled permanent magnet synchronous motor drive system to show the effectiveness and simplicity. A fault diagnostic technique to detect the fault type and fault location in multilevel inverter has been also proposed and validated [15]. A novel fast diagnostic method for open-switch faults in inverters without sensors has been proposed [16] to improve the reliability of the system. This scheme is achieved by the analysis using switching function model of inverter under both healthy and faulty conditions.

If an open-switch fault is not handled right away, it can induce secondary problems in the AC/DC PWM converter or other drive components, which ends up increasing the system repairing cost. Since the energy sources with high repairing cost are not desirable, it is very significant to monitor open-switch faults and recognize the faulty switch location correctly to reduce the repairing cost and improve the reliability and stability of system. Diagnostic method for the open-switch fault in a grid-connected neutral-point-clamped (NPC) inverter system was proposed in [17], which can detect and identify the open-switch fault within two fundamental periods. However, the research works dealing with the fault diagnosis in the presence of multiple open-switches without any false alarm are neither sufficient nor systematic. A cost-effective fault tolerant PMSG drive has been addressed with the ability to handle open-switch faults [18]. This technique does not require additional measurements and high computational efforts. An open-switch fault detection method by using the simple calculation and phase current without additional devices has been proposed for a back-to-back converter using NPC topology [19]. Another detection method with the fault-tolerant ability has been implemented for switching device in NPC inverter [20]. A two-level fault-tolerant voltage source inverter for permanent magnet drives was proposed [21], where the inverter provides tolerance to both short-switch and open-switch faults of the switching devices.

Field-programmable gate array (FPGA) based real-time diagnosis for power converter failure has been developed in WECSs [22]. An online basis fault detecting scheme of an inverter-fed permanent magnet synchronous motor drive system was presented to detect open-switch faults [23], which was based on monitoring the second order harmonic component in the quadrature axis current through the harmonic analysis. A model-based fault detection and isolation has been made to diagnose actuator faults in power inverters for induction motor under single and simultaneous faults [24]. The detection and identification of open-switch faults in IGBT using the wavelet decomposition have been developed for a direct torque control scheme of induction motor [25].

To solve the false alarm situation, this paper proposes new on-line multiple open-switch fault detection and faulty switch identification algorithms which can detect the open fault in single as well as in multiple switches without any false alarm. The proposed fault diagnosis scheme does not require any additional sensor. Furthermore, it is very simple and fast to detect such a fault. The reliability and effectiveness of the proposed fault diagnostic methods are proved through the simulations under various open-switch faults. The remaining parts of this paper are arranged as follows: Section 2 describes the fault detection algorithm of the proposed scheme. Then, Section 3 describes the faulty switch identification algorithm. In Section 4, the superiority of the proposed method is demonstrated through simulation results. Finally, Section 5 presents the conclusions.

2. Proposed Fault Detection Method

A flow chart of the proposed fault detection algorithm is presented in Figure 1. In the proposed fault detection algorithm, three-phase voltages V_a, V_b, and V_c are calculated at first by using the DC link voltage and switching times from the space vector PWM scheme.

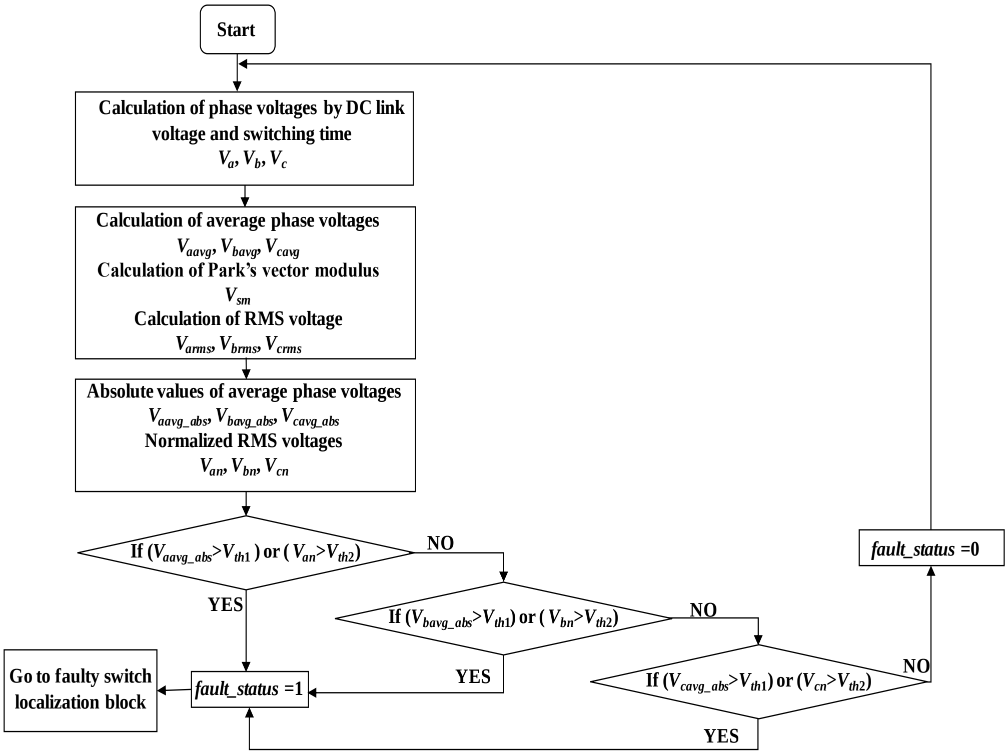
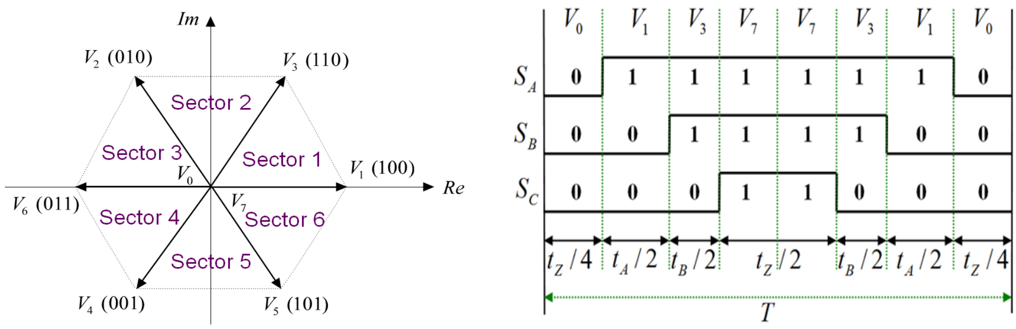


Figure 1. Flow Chart of the Proposed Open-Switch Fault Detection Algorithm

From these values, the absolute values of average three-phase voltages V_{aavg_abs}, V_{bavg_abs}, and V_{cavg_abs} and the normalized three-phase RMS voltages V_{an}, V_{bn}, and V_{cn} are calculated by using three-phase RMS voltages and Park's vector modulus. The switching pattern in the symmetrical space vector PWM scheme is shown in Figure 2.



(a) Sector and Space Voltage Vector (b) Switching Pattern

Figure 2. Switching Patterns in the Symmetrical Space Vector PWM Scheme

Table 1 shows the three-phase voltages in the AC/DC PWM converter, which are calculated by using the DC link voltage and switching times for six sectors. In Table 1, V_{DC} represents the DC link voltage, T is the switching period, t_A and t_B are the time duration of active vectors for each sectors, respectively, and t_z is the time duration of zero vector.

Table 1. Determination of Three-Phase Voltages for Each Sector

Sector	Three-phase voltages
Sector 1 Active Vectors V_1, V_3	$V_a = \frac{(2/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$, $V_b = \frac{(-1/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$ $V_c = \frac{(-1/3)V_{DC} \cdot t_A + (-2/3)V_{DC} \cdot t_B}{T}$
Sector 2 Active Vectors V_3, V_2	$V_a = \frac{(-1/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$, $V_b = \frac{(2/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$ $V_c = \frac{(-1/3)V_{DC} \cdot t_A + (-2/3)V_{DC} \cdot t_B}{T}$
Sector 3 Active Vectors V_2, V_6	$V_a = \frac{(-1/3)V_{DC} \cdot t_A + (-2/3)V_{DC} \cdot t_B}{T}$, $V_b = \frac{(2/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$ $V_c = \frac{(-1/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$
Sector 4 Active Vectors V_6, V_4	$V_a = \frac{(-1/3)V_{DC} \cdot t_A + (-2/3)V_{DC} \cdot t_B}{T}$, $V_b = \frac{(-1/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$ $V_c = \frac{(2/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$
Sector 5 Active Vectors V_4, V_5	$V_a = \frac{(-1/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$, $V_b = \frac{(-1/3)V_{DC} \cdot t_A + (-2/3)V_{DC} \cdot t_B}{T}$ $V_c = \frac{(2/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$
Sector 6 Active Vectors V_5, V_1	$V_a = \frac{(2/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$, $V_b = \frac{(-1/3)V_{DC} \cdot t_A + (-2/3)V_{DC} \cdot t_B}{T}$ $V_c = \frac{(-1/3)V_{DC} \cdot t_A + (1/3)V_{DC} \cdot t_B}{T}$

The three-phase voltages in the PMSG are transformed into the values on the stationary reference frame as follows:

$$V_d = \frac{2}{3}V_a - \frac{1}{3}V_b - \frac{1}{3}V_c\,,\ V_q = \frac{1}{\sqrt{3}}(V_b - V_c)\,. \tag{1}$$

Using these values, the Park's vector modulus V_{sm} is obtained by

$$V_{sm} = \sqrt{V_d^{\,2} + V_q^{\,2}}\,. \tag{2}$$

Three-phase RMS voltages of the generator are normalized by using this Park's vector modulus as follows:

$$V_{an} = \frac{V_{arms}}{V_{sm}},\ V_{bn} = \frac{V_{brms}}{V_{sm}},\ V_{cn} = \frac{V_{crms}}{V_{sm}} \quad \textbf{(3)}$$

where V_{arms}, V_{brms}, and V_{crms} are three-phase RMS voltages, respectively, and V_{an}, V_{bn}, and V_{cn} are the normalized three-phase RMS voltages, respectively. To detect open-switch fault, absolutes of average phase voltages and normalized three-phase RMS voltages are used. By using these two voltage informations as detection variables, a much more reliable and effective fault detection is possible under various open-switch faults even in low operating speed.

When the system is under the normal condition, the possible values for the absolute of average three-phase voltages and the normalized RMS voltage are zero and 0.5, respectively. On the other hand, these voltages are varied according to the location of the open-switch fault. To detect the open-switch faults effectively without false alarm, the defined threshold values are chosen as V_{th1}=20.0 and V_{th2}=1.0, respectively. Under the open-switch fault conditions, the detection variables which are V_{aavg_abs}, V_{bavg_abs}, V_{cavg_abs}, V_{an}, V_{bn}, and V_{cn} are remarkably increased beyond these thresholds. As is shown in Figure 1, the open-switch faults are detected as soon as one of these detection variables exceeds the thresholds V_{th1} and V_{th2}, setting the flag variable "*fault_status*" as 1 to indicate the occurrence of fault.

3. Proposed faulty Switch Identification Algorithm

The configuration of a wind power converter consisting of two power electronic converters with switch symbols is shown in Figure 3. The single open-switch fault in S_1 and the multiple open-switch faults in (S_1, S_3), (S_2, S_5), (S_3, S_5) are shown in Figure 3.

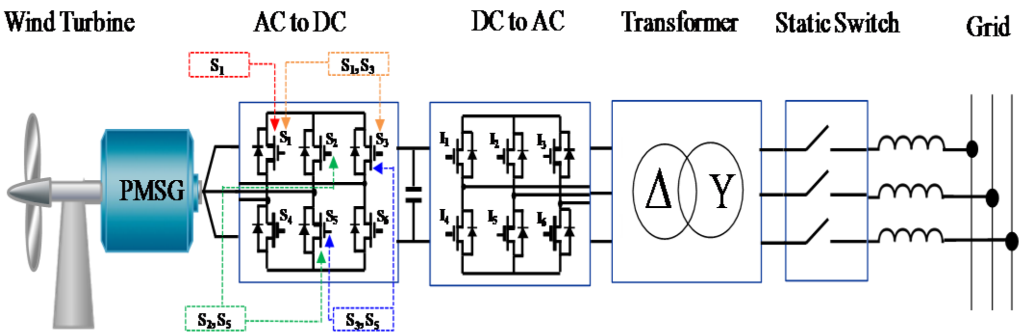


Figure 3. Configuration of a Wind Power Converter

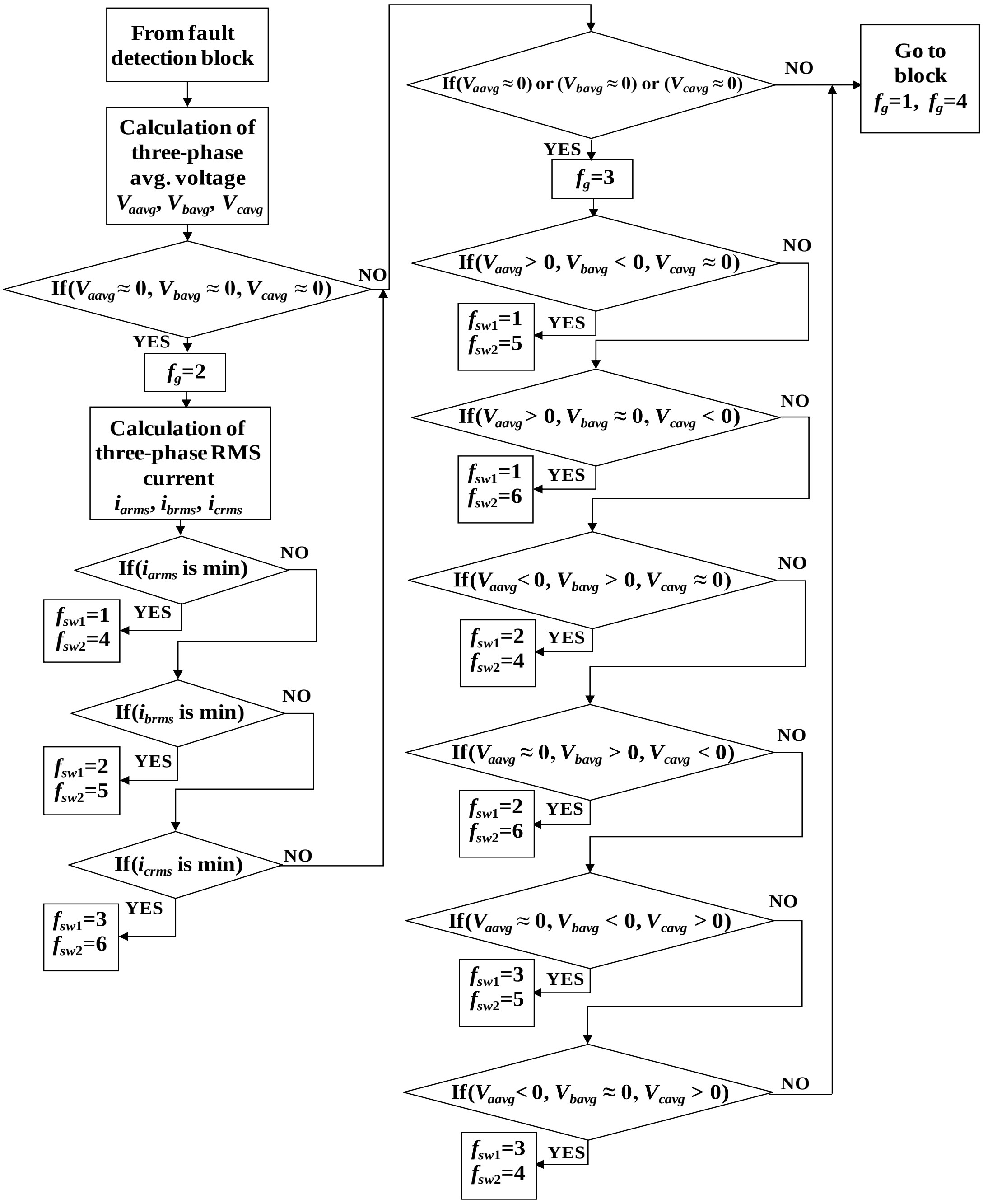


Figure 4. The Proposed Faulty Switch Identification Algorithm for f_g=2 and f_g=3

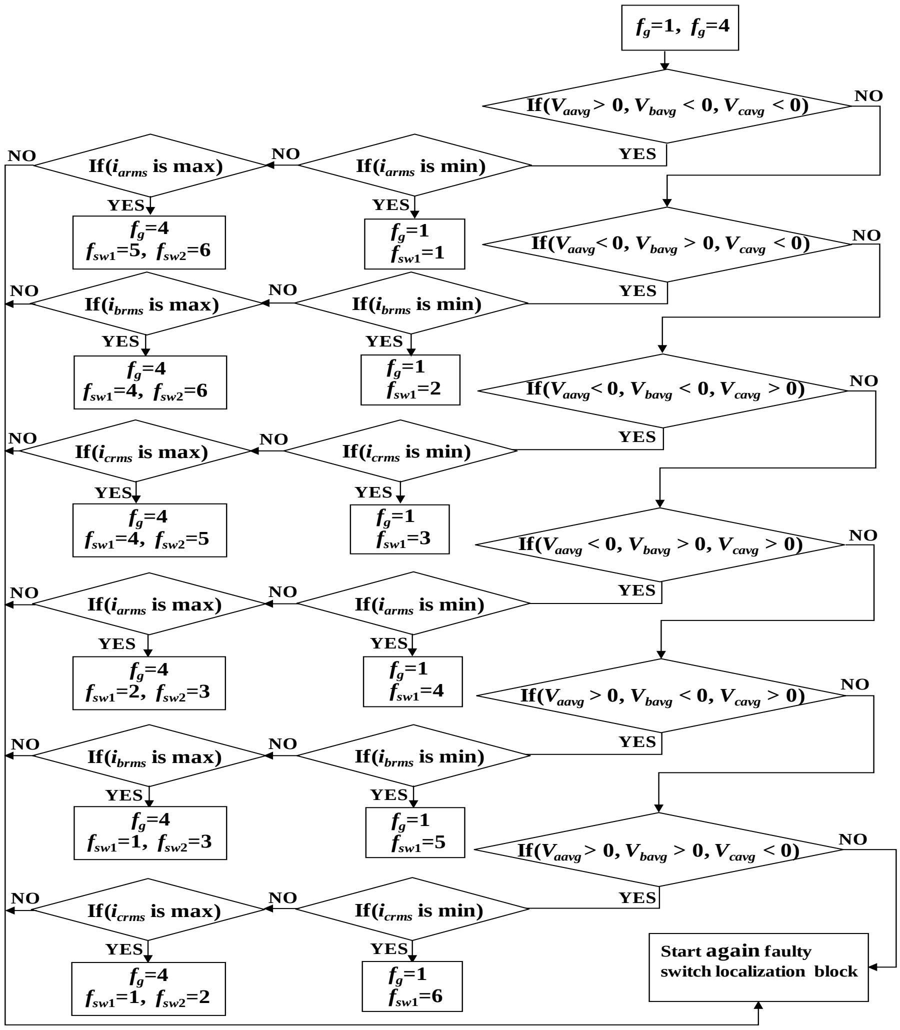


Figure 5. The Proposed Faulty Switch Identification Algorithm for f_g=1 and f_g=4

In this paper, total twenty-one cases of the open-switch fault are considered including the open-switch fault either in single switch or two multiple switches. While the case of the single open-switch fault constitutes one group, the case of multiple open-switch faults is composed of three groups. According to this, twenty-one cases of the open-switch faults are categorized as four faulty groups depending on the position of faulty switches. The first group is the case of the open-switch fault in single switch. The second group is the single-phase open-switch fault (open fault in two switches of the same converter leg). There are two more groups for multiple open-switches fault. The third group is the case having two open-switches, one in upper leg and the other in different lower leg. The last group is the case having two open-switches, either only in upper leg or only in lower leg. To deal with these four faulty groups effectively, the faulty group is defined with their elements as follows:

f_g=1 $\{(S_1, S_2, S_3, S_4, S_5, S_6)\}$

f_g=2 $\{(S_1, S_4), (S_2, S_5), (S_3, S_6)\}$

f_g=3 $\{(S_1, S_5), (S_1, S_6), (S_2, S_4), (S_2, S_6), (S_3, S_5), (S_3, S_4)\}$

f_g=4 {(S_5, S_6), (S_4, S_6), (S_4, S_5), (S_2, S_3), (S_1, S_3), (S_1, S_2)}.

The flow charts of the proposed faulty switch identification algorithm are shown for respective faulty groups in Figure 4 and Figure 5.

4. Simulation Results

To verify the proposed method, a PMSG-based wind power system with the grid connection was built by using the PSIM software. The proposed diagnosis scheme has been tested by considering an open-switch fault in single and multiple cases.

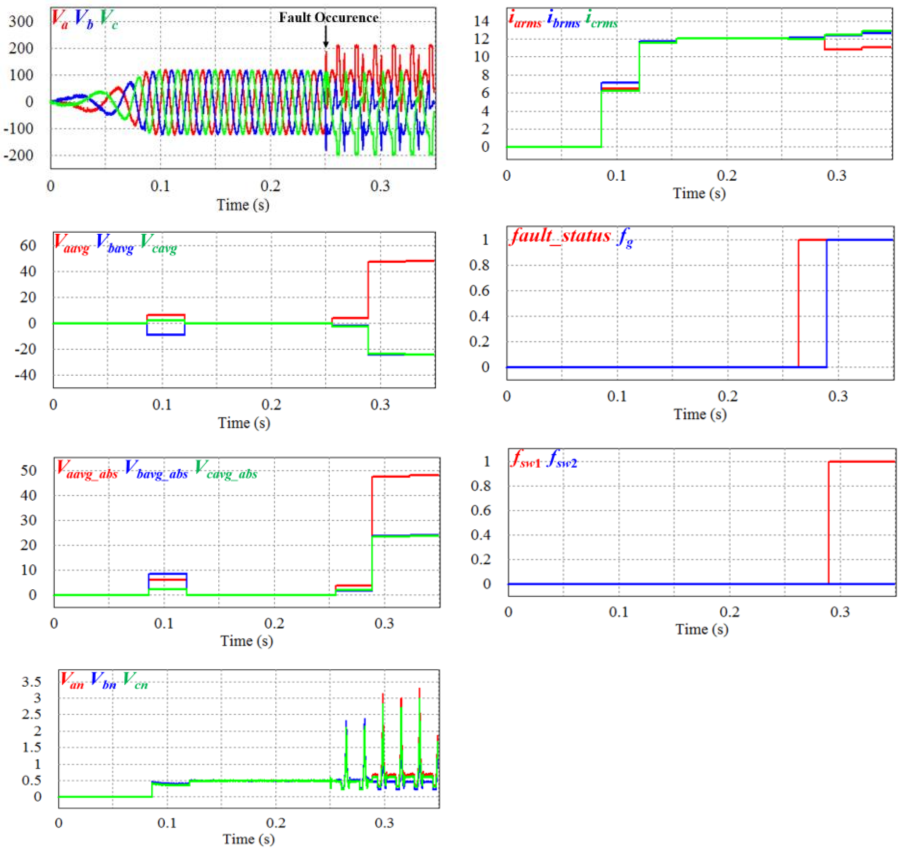


Figure 6. Simulation Results under S_1 open-switch Fault (300 rpm Operations)

First, the case of an open-switch fault in S_1 of Figure 3 is considered. The switch S_1 located on the upper leg of *a*-phase is removed at t=0.25 sec. During the normal operation, the normalized RMS voltage values become 0.5 and the absolute values of average three-phase voltages become zero. However, as soon as the fault occurs, six detection variables are increased much beyond these threshold values V_{th1} and V_{th2} as shown in Figure 6, which makes the variable "*fault_status*" change from zero to one. Once the open-switch fault is detected, the operating mode is changed to the faulty switch identification algorithm.

The faulty switch identification algorithm starts with the calculation of three-phase average voltages to investigate whether they are close to zero or not. As shown in Figure 6, because three-phase average voltages are not close to zero, the faulty group f_g=2 or f_g=3 are not satisfied. The diagnostic algorithm further investigates by using three-phase average voltages in Figure 5 to determine the faulty group f_g as 1. Once the faulty group is determined, the diagnostic algorithm identifies the faulty switch by finding the phase having the minimum RMS currents. Since *a*-phase RMS current is minimal in Figure 6, the detection algorithm concludes that the faulty switch is S_1.

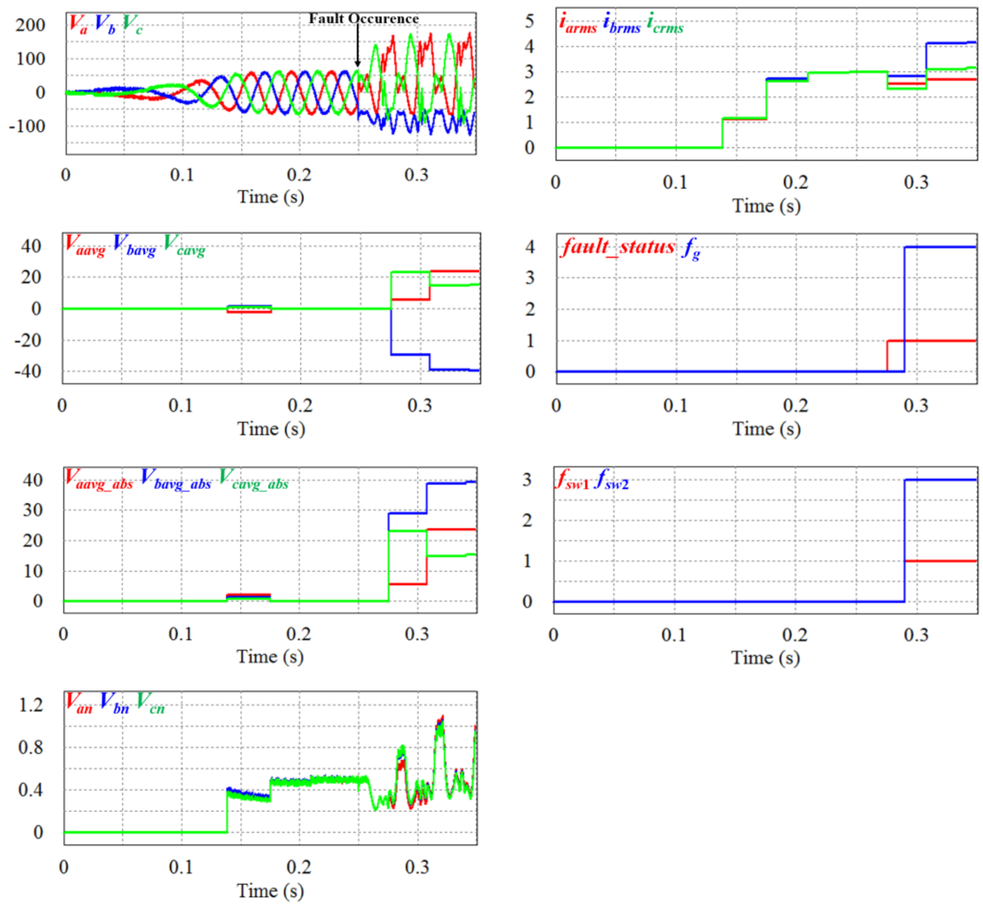


Figure 7. Simulation Results under S_1 and S_3 open-switch Fault (150 rpm Operations)

Next, the case of the open-switch faults in S_1 and S_3 of Figure 3 is examined. The open-switch fault in S_1 and S_3 belongs to the last faulty group, where two open-switches occur only in the upper leg of converter. Figure 7 shows the simulation results for this condition at 150 rpm. Similarly, as soon as the open-switch fault occurs at 0.25 sec, the detection variables are immediately increased beyond the threshold values, changing “*fault_status*” to one as shown in Figure 7. Then, by investigating three-phase average voltages and three-phase RMS currents, the faulty switch identification algorithm determines the fault group f_g as four and the faulty switches f_{sw1} and f_{sw2} as one and three, respectively.

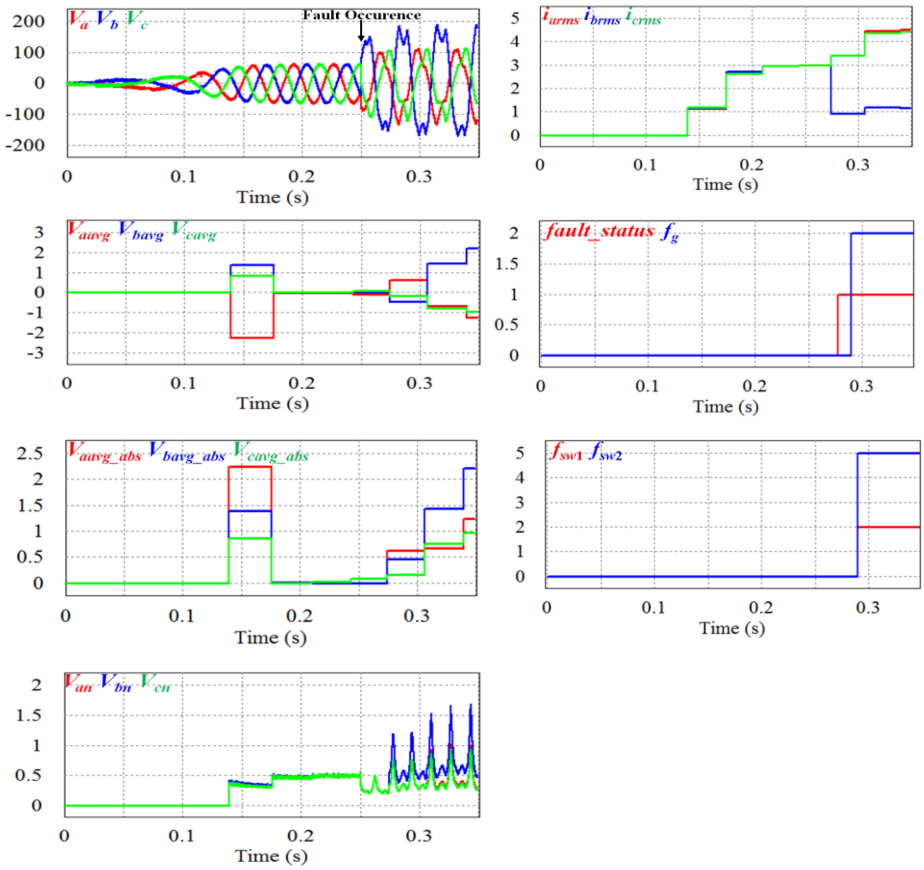


Figure 8. Simulation Results under S_2 and S_5 open-switch Fault (150 rpm Operations)

The next case is the single-phase open-switch fault when there are two open-switch faults in the same converter leg as S_2 and S_5. Figure 8 shows the simulation results for this fault condition at 150 rpm. It is shown in Figure 8 that *b*-phase voltage is much distorted due to the open faults in S_2 and S_5. The proposed algorithm can detect two open-switch faults in the same converter leg at the same time, as long as the value of V_{th2} is higher than the threshold value. Generally, this fault group has the feature that the three-phase average voltages are very small as compared with the other fault conditions as shown in Figure 8. This is the reason that the proposed diagnostic algorithm in Figure 1 uses the normalized RMS voltages together with the three-phase average voltages. Even though the average phase voltages cannot detect the fault due to smaller value than V_{th1}, the normalized RMS voltages can detect the fault by comparing this value with V_{th2}, even in this case. For this purpose, the average voltage in the range between -4 and 4 is assumed to be zero. After the fault detection, the faulty switch identification algorithm is examined to find out the faulty switches using Figure 4. By investigating three-phase average voltages and three-phase RMS currents, the proposed diagnosis algorithm determines the fault group f_g as two and the faulty switches f_{sw1} and f_{sw2} as two and five, respectively, as shown in Figure 8.

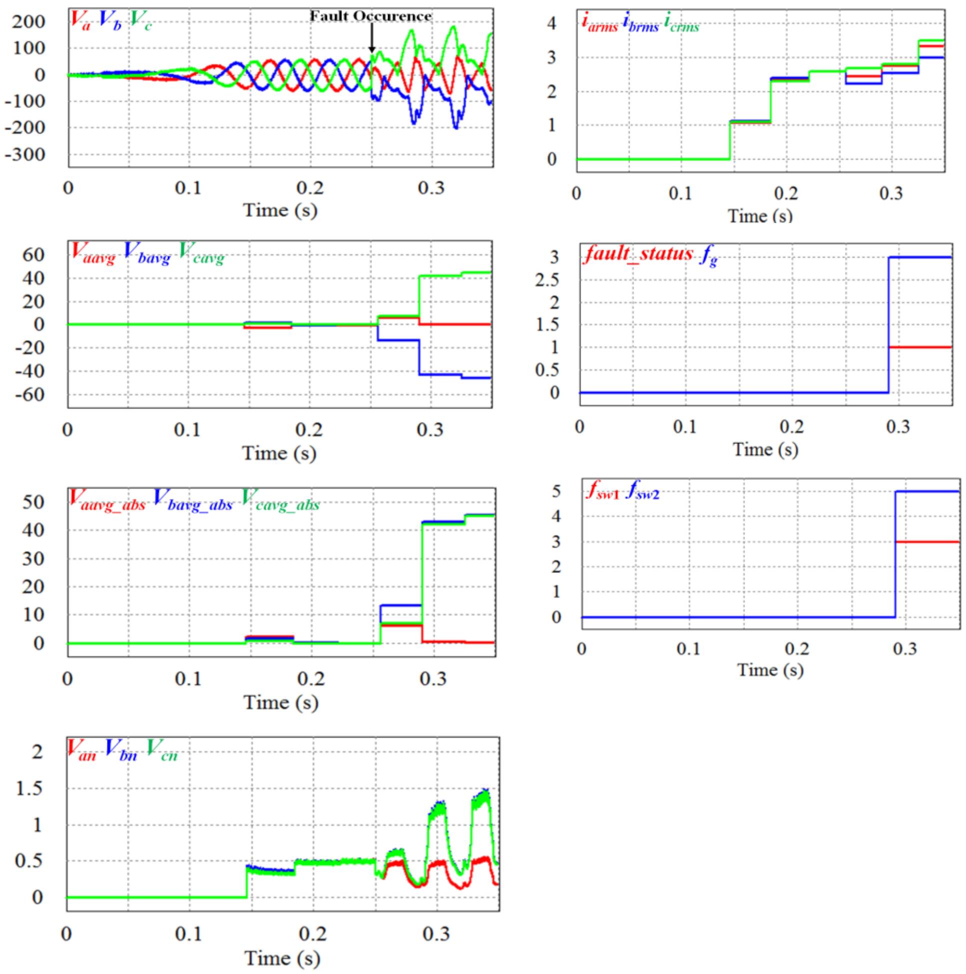


Figure 9. Simulation Results under S_3 and S_5 open-switch Fault (140 rpm Operations)

The last results for the case of the open fault in multiple switches are shown in Figure 9. This case has two open-switches, one in upper leg and the other in lower leg. Whereas the phase with the faulty switch in upper leg has positive average voltage, the phase with the faulty switch in lower leg has negative average voltage. On the other hand, the average phase voltage without faulty switch is close to zero. By using the similar process as presented in previous fault cases, the open fault can be detected successfully. By analyzing with voltage information, the proposed algorithm concludes that the faulty group f_g is three and the faulty switch variables f_{sw1} and f_{sw2} are three and five, respectively, as shown in Figure 9.

Even though the simulation results in Figure 6 through Figure 9 represent the detection results under only four fault conditions among twenty-one cases, the proposed algorithm works effectively under the other fault conditions. Table 2 summarizes the test results including other fault conditions, which proves that the proposed method successfully detects the open-switch faults and fault locations, even in these cases. Table 2 also represents the total time required for the fault detection and localization.

It has been proved through the simulation results that the reliability of the proposed scheme is significantly improved due to its independence on operating condition, robustness against the issue of false alarms, and fast detection time.

Table 2. Test Results Under 21 Cases of Open-Switch Faults

Faulty switches	Total time [ms]	f_q	f_{sw1}	f_{sw2}
S_1	59.7	1	1	None
S_2	25.9	1	2	None
S_3	25.9	1	3	None
S_4	25.7	1	4	None
S_5	25.7	1	5	None
S_6	58.5	1	6	None
S_1,S_4	32.4	2	1	4
S_2,S_5	27.1	2	2	5
S_3,S_6	24.9	2	3	6
S_1,S_5	24.9	3	1	5
S_1,S_6	26.4	3	1	6
S_2,S_4	24.9	3	2	4
S_2,S_6	24.9	3	2	6
S_3,S_5	25.2	3	3	5
S_3,S_4	25.2	3	3	4
S_1,S_2	25.4	4	1	2
S_1,S_3	25.9	4	1	3
S_2,S_3	24.6	4	2	3
S_4,S_5	24.3	4	4	5
S_4,S_6	24.8	4	4	6
S_5,S_6	25.5	4	5	6

5. Conclusions

In this paper, new voltage-based on-line fault detection and faulty switch identification algorithms under multiple open-switches are presented for a grid-connected wind power converter. The proposed algorithms are based on the three-phase voltages which are calculated by using the DC link voltage and switching times determined from the space vector PWM scheme. As compared with the existing methods, the proposed scheme has a high immunity against the issue of false alarm since it does not depend on load current or operating conditions. Furthermore, the complete diagnosis algorithms are carried out by a simple method during operation, which does not require any additional sensors. To verify the validity of the proposed method, a PMSG-based wind power system with the grid connection has been built by using the PSIM software. The proposed diagnosis scheme has been tested at different operating conditions under twenty-one cases of open-switch faults including the case of multiple open-switches. As a result, the proposed scheme can effectively detect the occurrence of fault as well as faulty switches for these conditions independent of operating conditions with a relatively simple computational algorithm, which leads to a cost-effective and reliable realization of a distributed generation system.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2012R1A1A2042759).

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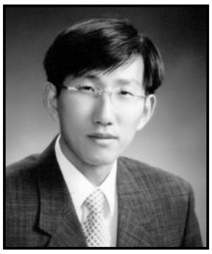

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