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An Open Circuit Fault Diagnostic Technique in IGBTs for AC to DC Converters Applied in Microgrid Applications

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Abstract

An open circuit fault diagnostic method in IGBTs for the ac to dc converters used in microgrid applications is developed in this paper. An ac to dc converter is a key technology for microgrids in order to interface both distributed generation (DG) and renewable energy resources (RES). Also, highly reliable ac to dc converters are necessary to keep converters in continuous operation as long as possible during power switch fault conditions. Therefore, the proposed fault diagnostic method is developed to reduce the fault detection time and to avoid any other fault alarms because continuous operation is desired. The proposed diagnostic method is a combination of the absolute normalized dc current technique and the false alarm suppression algorithm to overcome the long fault detection time and fault alarm problems. The simulation and experimental results show that the developed fault diagnostic method can perform fault detection within about one cycle. The results illustrate that the reliability of an ac to dc converter interfaced with a microgrid can be improved by using the proposed fault diagnostic method.

Key Words: Distributed generation, Fault diagnosis, Microgrid, Power electronics

I. Introduction

Renewable energy resources (RES) have had increasing levels of penetration for grid connected distributed generation (DG) in recent years. Photovoltaic, microturbine, wind turbine, and fuel cells put forward many promising applications with high efficiency and low emissions. Together with power electronics technologies, they have produced an important improvement for RES and DG applications. A microgrid concept is introduced in [1] to provide greater system capacity and control flexibility when several RESs with different electric behaviors are integrated into the same grid. The microgrid also offers extra degrees of freedom to optimize RESs connected to the utility grid. Additionally, power quality requirements, system reliability, and control flexibility can be achieved by using the microgrid concept discussed in [2].

The main concept of a microgrid that differs from a conventional utility grid is that the power generators are small; usually, a small DG or RES. These DGs and RESs are located close to the load (end users or consumers). Then, the generator and the load can be managed to achieve a local energy and power balance. A possible structure of a microgrid for local energy management is illustrated in Fig. 1. One can see that photovoltaic cells, a doubly-fed induction generator and a combined heat power (CHP) generator are the small distributed generators supplying energy to the microgrid. A CHP system uses natural gas to produce heat and electricity simultaneously. The electricity can be used for any household device such as lights and appliances. A 6-kW unit can offer 40 l/min of hot water at about 65 °C. This waste heat can be used to heat an entire home, to supply water for family use or for swimming pools, or even as an energy source for heat-driven (absorption) cooling systems. A CHP for residential use is shown in Fig. 2. CHP systems are extremely efficient, offering a combined heat and power generating efficiency of about 90%, compared to about 30 to 40% for electricity from a central power station. In addition, as can be seen from Fig. 1, a flywheel machine is used for energy storage. The load is represented by an induction motor drive together with conventional and sensitive loads.

Fig. 1 also shows that the power electronic devices used in a microgrid consist of both inverters (dc to ac) and rectifiers (ac to dc). Clearly, power electronics play an important role in the

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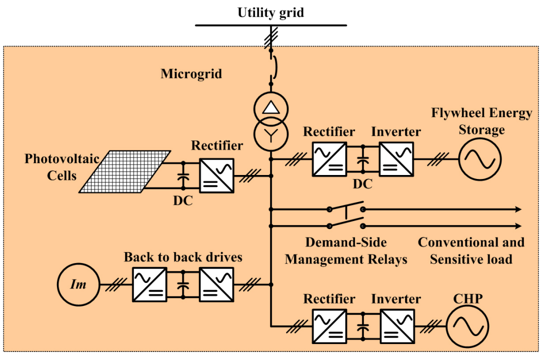


Fig. 1. Microgrid for a local energy system.

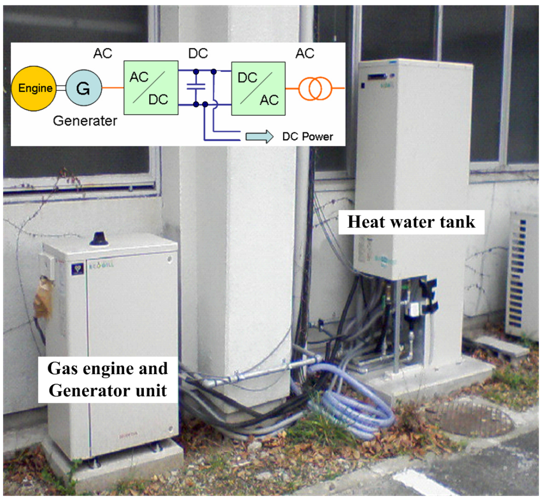


Fig. 2. Combined heat power for residents.

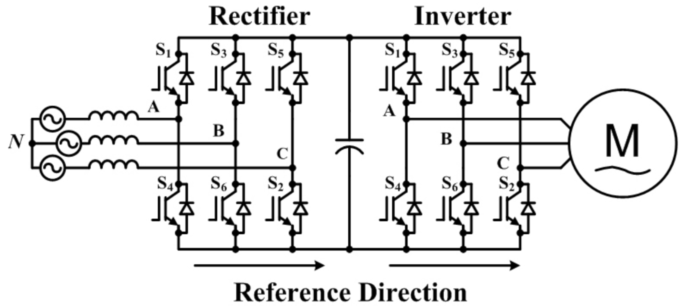


Fig. 3. The induction motor drive with a back-to-back converter.

control of voltage and power between the microgrid and the DGs. Therefore, the reliability of both inverters and rectifiers is very important. If a single switch has a fault in either an inverter or a rectifier, the DGs will be required to stop their operation. As a result, the energy provided to the microgrid will decrease simultaneously. This will lead to voltage and frequency fluctuation problems. Normally, passive protection, such as fuses or over current circuits in the intelligent power module, is used to protect the switching devices. These passive protection devices will disconnect the power sources or the gate drive signals from the inverter system whenever a fault occurs, stopping the operated process. It would be better if a fault and its location can be detected. Then, the switching patterns and the modulation index of the other active switches of the inverter can be modified to maintain operation under a balanced load condition. Of course, the inverter/rectifier cannot be operated at its full rated power. The amount of reduction in the rated power that can be tolerated depends upon the inverter application. Nevertheless, in most cases, a reduction in the rated power is preferable to a complete shutdown. For the case of short circuit switch fault, the fault needs to be cleared as quickly as possible. Under this condition, continuous operation may not be achieved. However, in some cases, a short circuit switch might be in this state for a short time before burning open and becoming an open circuit switch fault.

Research on fault diagnostic techniques initially focused on conventional PWM voltage source inverters (VSI). The various fault modes of a VSI system for an induction motor were investigated in [3]. The integration of a fault diagnostic system into VSI drives is described in [4]. This integrated system introduced remedial control strategies shortly after failure occurrences. Therefore, system reliability and fault tolerant capability are improved. A noninvasive technique for diagnosing VSI drive failures based on the identification of unique signature patterns corresponding to the motor supply current Park's Vector is proposed in [5], [6]. A comparison of the features, cost, and limitations of fault-tolerant three-phase AC motor drive topologies is investigated in [7]. Many fault diagnostic methods for an inverter based on the time domain and the frequency domain have been proposed in [8]–[15]. In [11], [15], fault detection for an active rectifier is also discussed.

One can see from this literature survey that knowledge of and information on fault behaviors in inverters and rectifiers is important for improving system design, protection, and fault tolerant control. Thus far, limited research has focused on rectifier or ac to dc converter fault diagnosis for microgrid applications, which require wide range of speeds due to the different types of DGs. For instance, the machines for CHPs, microturbines, and wind turbines may operate from sub synchronous to super synchronous speeds. Therefore, a fault diagnostic method for the ac to dc converters used in microgrid applications is developed in this paper. The developed technique is a combination of the absolute normalized dc current technique and the false alarm suppression algorithm. The proposed fault diagnostic method can reduce the detection time and avoid any other false alarms. As a result, continuous operation can be achieved.

II. Fault Analysis and Previous Diagnostic Techniques

A. *Open-Switch Fault in a Closed-Loop PWM Rectifier*

A PWM rectifier is generally used in a regenerative induction motor drive system by connecting back-to-back with a PWM inverter as shown in Fig. 3. The main tasks of this converter are to control the active and reactive power flowing through the grid, to improve the grid power quality, and to regulate the dc-link voltage.

In some applications, such as power generation systems, the PWM converter on the generator side, which is generally used to control the generator, also works in rectifier mode allowing for a power flow from the ac-side to the dc-side.

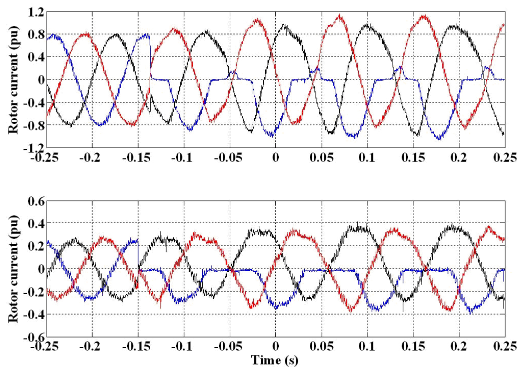


Fig. 4. The diode current appearing in the faulted phase current (top) rectifier mode, (bottom) inverter mode.

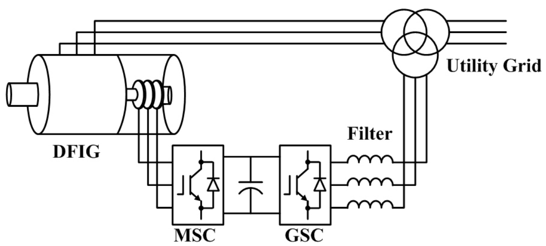


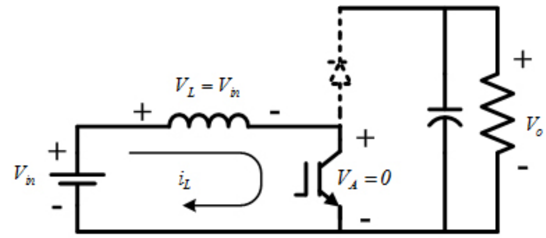
Fig. 5. Simplified diagram of a doubly-fed induction generator.

Under open-switch fault conditions in the PWM rectifier, the current in the faulty leg does not remain zero as in the case of a PWM inverter. Current can flow through the anti-parallel diode associated with the faulty switch, allowing the current to flow in during the fault's first half cycle, as shown in Fig. 4. The waveforms shown in Fig. 4 are the rotor current waveforms of the doubly-fed induction generator (DFIG) shown in Fig.5, operating at 1.2 pu (super synchronous speed). The rotor power flows from the ac side to the dc side of the machine-side converter (MSC) meaning that the converter is operating under rectifier mode. The open circuit fault appears in the top switch of phase A. To explain this phenomenon, the operation of a dc-dc boost converter is considered. Generally, a PWM rectifier has the same operating scheme as a dc-dc boost converter. The operation starts by turning on a switch to charge an inductor, causing energy storage in the inductor as shown in Fig. 6(a). This duration is called the boost period. Once the switch is turned off, the energy stored in the inductor is released to the load through a diode, as in Fig. 6(b).

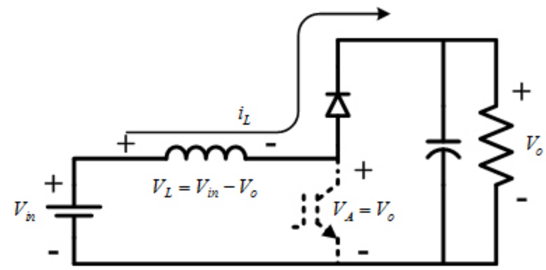
The semiconductor switch is thus responsible for boosting energy to the inductor, whereas the diode is responsible for freewheeling energy to the high voltage side. The same principle applies to a three-phase PWM rectifier. During the boost period of each phase for the positive current, the positive current from the ac source flows through the bottom IGBT and then via the diode of another phase it is connected to the same negative dc bus. The same operation for the negative current occurs with the top switch of the phase and the top diode of another phase.

To clearly explain the appearance of the diode current, the example of an open-switch fault at the top switch of phase A of a PWM rectifier is shown in Fig. 7. This converter's reference direction is from the ac-side to the dc-side. Generally, to build up the desired dc voltage, the switches are required to boost the energy in the inductor. Therefore, if the switch experiences an open circuit fault while its firing signal is high, the boost period is cancelled. Since the current flow through an inductor cannot stop immediately, the current of the faulted phase must find a path. The only path is through the diode that is associated with the faulted switch. If there was no path for this current, a voltage spike caused by $L\frac{di}{dt}$ would occur, resulting in damage to the converter.

The interpretation of this phenomenon is shown in Fig. 7. Beginning with the first command signal, 000, phase B of the converter is in the boost state; whereas, the other phases are in the freewheeling state. As explained previously, during the boost state the currents flowing through the phase B switch will flow to other phases connected to the same dc bus. Therefore, the sum of the currents through the other phases is



(a)



(b)

Fig. 6. Boost converter operation mode (a) boost mode, (b) freewheeling mode.

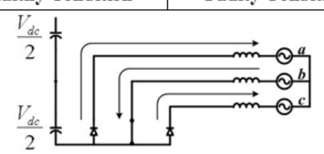
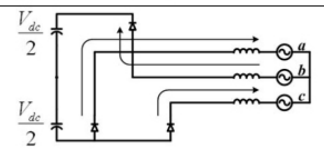
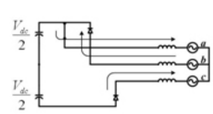
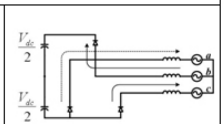
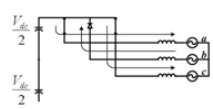
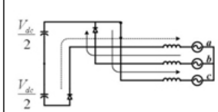
Signal	Healthy Condition	Faulty Condition
000		
010		
110		
111		

Fig. 7. The current flow diagram of the faulty converter.

equal to the current in the phase B inductor. During the second command, 010, all three phases are in the freewheeling state. The current flowing in the phase A is equal to $i_b - i_c$.

During command 110, the phase A top switch should conduct current, and phase A should be in the boost state. However, because of the open-switch fault, the boost period is cancelled. Since the current flowing through the inductor cannot stop immediately, the freewheeling state is maintained.

In the last command, 111, phase C is in the boost state and its current flows through phase B, while the phase A inductor discharges energy during this command. The sequence of operation returns to commands 110 and 010, which maintain the freewheeling period of phase A. Under command 000, phase B becomes boosted again, and the phase A inductor is charged again. Since the software for closed-loop operation is designed to minimize errors, under faulty conditions the modulating signal is affected. It prolongs the sector that is occupied by the faulted switch, and the charging period (000 states) becomes longer than usual. Therefore, the current flowing through the diode is built up until the diode continuously conducts current, as shown in Fig. 4.

This phenomenon does not appear in the case of an inverter because the main task of the inductor is to act as a filter. The operation is similar to a buck converter. While operating away from a unity power factor, the diode peak current is reduced because, for each half cycle, the converter operates in both inverter and rectifier modes. There is not enough time for the rectifier mode to maintain the current flow through the related diode.

B. Effect of an Open-Switch Fault in a Converter

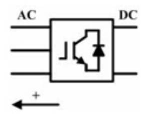
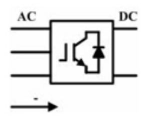
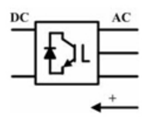
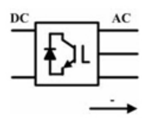
Each converter is controlled by vector control but orientated to different reference frames. Moreover, the reference direction of the current flowing through each converter is different. Generally, one converter is an inverter, while the other converter is a rectifier. The inverter and the rectifier have different current reference directions because of their operating modes. Therefore, when a fault occurs in a switch having the same location the result may be different.

For simplicity of analysis, knowledge of the reference direction is necessary. The reference frame, the reference direction and the conducting devices for each fundamental half cycle are shown in Table I. Normally, under open-switch fault conditions, the converter faulty phase current loses one half a cycle, as shown in Fig. 4. This figure shows an open-switch fault in the phase A top switch. As shown in Table I, the reference current directions of the converters are different. Therefore, the missing half cycle of each case is different. Depending on which switch is conducting, at synchronous speed generation, this fault will not be visible if the current is not conducted by the faulty switch. If the DFIG remains operating at synchronous speed, the fault will never appear on the faulty phase current.

C. Open-Switch Fault Diagnostic Method

Thus far, several diagnostic methods have been discussed [5]–[15]. However, only the following digital signal processing-based techniques are considered here:

TABLE I
CONDUCTING DEVICES OF EACH CONVERTER FOR CURRENT FLOWING IN THE REFERENCE DIRECTION AND IN THE REVERSE DIRECTION

Reference direction	Current Direction	Switching Command	Conducting Devices
DC-to-AC		1	Top Switch
		0	Bottom Diode
		1	Top Diode
		0	Bottom Switch
AC-to-DC		1	Top Diode
		0	Bottom Switch
		1	Top Switch
		0	Bottom Diode

- Slope Method [8], [9]
- Park's Vector Method [10], [11]
- Control Deviation Method [12]
- Normalized DC Current Method [13]
- Modified Normalized DC Current Method [6], [15]
- Simple DC Current Method [6], [15]

The advantages and drawbacks of these methods are discussed in [6], [15]. The most significant problem identified was the presence of false alarms. This was partially resolved by introducing a fixed dead time for each method [15]. However, this did not prevent false alarms under every operating condition. A fixed dead time can be used in a grid-side converter but not in a machine-side converter which has a variable fundamental frequency. This is one of the weaknesses of the existing fault detection methods.

With the exception of the slope method, each method is based on a calculation of the dc component and/or fundamental component of either the space vector of the three-phase currents or of all the three phase currents, and this is used as a diagnostic index. A recursive moving average technique is employed to achieve the calculation of these indices. However, in the case of a machine-side converter, the frequency of the currents varies through zero frequency. Under this condition, when the speed of the generator passes the synchronous speed, only the slope method and the control deviation method do not show false alarms. The park's vector method, the normalized dc current method, the modified normalized dc current method, and the simple dc current method show false alarms under this condition, due to the nature of their moving average calculations. This requires the previous instantaneous data for the present moving average value.

In the case of N samples per cycle, the present average value needs the present value and $N-1$ previous values for calculation. When the machine passes synchronous speed, the current becomes dc. Depending on the rate of change in speed, the fundamental component of the current is zero or almost zero for a certain time. This causes the average and normalized average values to become very high after the speed passes synchronous speed.

The control deviation method does not suffer from false alarms under these conditions because there is no fundamental component in the command current. However, it has false alarms under transient conditions and under low current conditions. Moreover, the fault detection algorithm must be integrated into the control algorithm.

The slope method does not perform well at fault detection as described in [6], [15]. It has a longer detection time when compared with the other methods because the slope method has some values in the tolerance range of faulty states under healthy conditions [15]. As illustrated in [6], [15], the modified normalized dc current method is the most effective of the existing methods. It was first proposed by Abramik *et al.* [6] and it was later modified by Rothenhagen and Fuchs [6], [15]. This method uses the moving average value of the line current as a diagnostic variable. To make this variable independent of the load, the moving average value is normalized by the fundamental component of the line current by means of the Discrete Fourier Transform (DFT), as shown in the equations below:

$$\mu_v = \frac{1}{N}\sum_{k=1}^{N} I_v(k\tau), \tag{1}$$

$$I_{1,v} = a_{1,v}\cos\left(\frac{2\pi}{T}k\tau\right) + b_{1,v}\sin\left(\frac{2\pi}{T}k\tau\right), \tag{2}$$

$$\gamma_v = \frac{\mu_v}{I_{1,v}} \tag{3}$$

$$a_{1,v} = \frac{2}{N}\sum_{k=1}^{N} I_v(k\tau)\cos\left(\frac{2\pi k}{N}\right) \tag{4}$$

$$b_{1,v} = \frac{2}{N}\sum_{k=1}^{N} I_v(k\tau)\sin\left(\frac{2\pi k}{N}\right) \tag{5}$$

$$v \in [a,b,c] \tag{6}$$

$$\frac{1}{f} = N\tau \tag{7}$$

where k is 1, 2, 3…64, N is 64, and γ_v is a diagnostic variable for the modified normalized dc current method of each phase.

Under healthy conditions, the value of γ_v is always within the threshold of 0.45 [6], [15]. However, under faulty conditions, the value of γ_v for the faulty phase exceeds the threshold. When the value of γ_v exceeds the threshold in more than one phase, the phase with the highest absolute value of γ_v is the faulty phase.

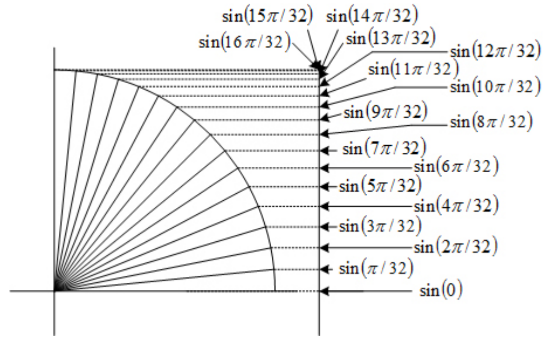


Fig. 8. The first sector of a unit circle used for calculation of the faulty band for current during a faulty half cycle.

III. Proposed Fault Diagnostic Method

The normalized dc current method [13] and the modified normalized dc current method [6], [15], explained earlier, are time consuming and need DFT calculations. To reduce the burden on the DSP, an alternative diagnostic variable is proposed. Moreover, since the objective of introducing fault detection is to improve reliability, any false alarm must be avoided. Therefore, in this section, an alternative method to detect and locate faults, while overcoming the false alarm problem is presented. In this paper, an absolute normalized dc current method [16] is proposed to solve the problems.

According to the sampling technique proposed by Abramik *et al.* [13], a signal is sampled N times in one period with a fixed angular step between the samples as shown in Fig. 8.

By dividing a unit circle into 4 sectors, and considering only the first sector as shown in Fig. 8, each sector contains 16 samples with a value of $\sin(2m\pi/N)$, where m is 1, 2, 3,…, 16 and N is 1, 2, 3,…, 64.

A. Absolute Normalized DC Current Method

This method uses an algorithm similar to the modified normalized dc current method, but instead of using the fundamental component as a normalizing variable, it uses the average of the absolute values of each phase current. Under faulted conditions, the faulted phase current has only one half a cycle, so the normalized average value is equal to 1. Using this method, only the calculation of the absolute value is required. This method requires less computational time and has a reduced firmware code size for fault detection. A threshold of **0.65** was found to be suitable for both the simulation and the experiment. Also, this threshold is independent of the load condition because it is calculated from the ratio of the input currents. The equations used to calculate the diagnostic variable for this method are the average value of the current as shown in (1) together with (8) and (9) as follows:

$$\lambda_v = \frac{1}{N}\sum_{k=1}^{N} |I_v(k\tau)| \tag{8}$$

$$\xi_v = \frac{\mu_v}{\lambda_v} \tag{9}$$

where ξ_v is the diagnostic variable of the absolute normalized dc current method for each phase.

As shown in Fig. 9(a), the phase A top switch is open and therefore it loses the positive half cycles. The values of ξ_v after an open-switch fault in the machine-side converter operating in the inverter mode are shown in Fig. 9(b). The value of ξ_v of phase A exceeds the threshold and saturates at± 1; whereas, the values of ξ_v of phases B and C still lie within the threshold. This figure proves that ξ_v can be used as a diagnostic variable in the same way as γ_v.

The result from Fig. 9 shows that the proposed diagnostic variable can correctly perform fault detection and that the absolute normalized dc current method can also reduce the computational time for the fault detection module. However, the major problem of false alarms still exists. This problem can be solved by using a false alarm suppression algorithm.

Due to the periodic nature of ξ_v, as shown in Fig. 10, if a DFIG operates at or around synchronous speed, the value of ξ_v may exceed the threshold for at least 1/3 of a cycle. This periodic nature can be used in a false alarm suppression algorithm. To avoid false alarms, a delay of one half a cycle ($^N/_2$ points) is introduced. During this delay, if the value of ξ_v for one of the other phases also exceeds the threshold, all of the phase fault flags are set to zero. As a result, no false alarms appear although the speed of the generator swings slightly around synchronous speed. With this algorithm, the problem of operating a DFIG around synchronous speed or passing through synchronous speed is completely solved. It should be noted that this false alarm suppression algorithm may not be required for other ac to dc converter applications. For instance, the CHP and the constant speed prime mover types. This false alarm suppression algorithm can be applied together with the absolute normalized dc current method. The algorithm can be represented in a flowchart as shown in Fig. 11. To achieve false alarm suppression, as shown in Fig. 11, the variable $acc\xi_v$ is introduced as an accumulator. It is updated at every interrupt for checking whether the absolute value of the diagnostic index is larger than the threshold (0.65) for a longer time than the delay value. If this value is larger than the delay value, the accumulator is set to the value called Max $acc\xi_v$, as depicted in Fig. 11.

Finally, the output of this method will be used for system reconfiguration as clearly investigated in [7]. This method can also be applied to four quadrant electrical motor drives where the motor changes direction [16].

IV. Simulation and Experiment Validation

A. Simulation Results

MATLAB/SIMULINK is used to simulate the back to back inverter as shown in Figs. 3 and 14. The simulation results in Figs. 12 and 13 show that the time required to detect the fault in each case is approximately one cycle. From these figures, the fault appears approximately in the middle of the cycle conducted by the faulty switch. Creating a fault at this point is done to investigate the maximum time required for each of the fault detection algorithms. The fault is applied at the same point on the current waveform for both fault detection algorithms. The simulation results in Figs. 12 and 13 show that the time required to detect the fault in each case is similar for the absolute normalized dc current method and the modified normalized dc current method. As previously

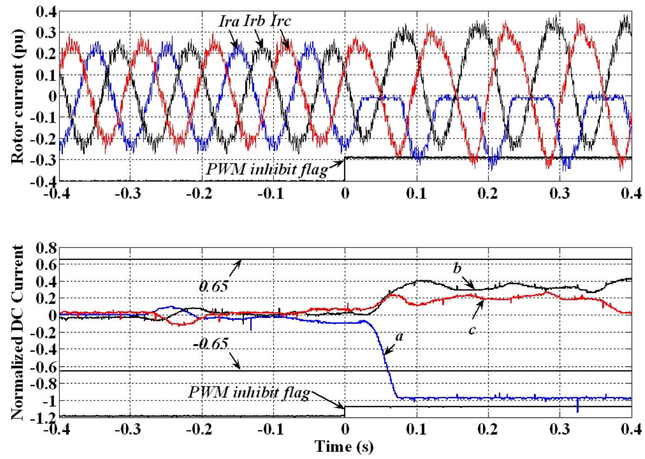


Fig. 9. Experimental results showing (top) rotor currents and (bottom) the value of the diagnostic variables of the absolute normalized dc current method under an open-switch fault in the inverter mode.

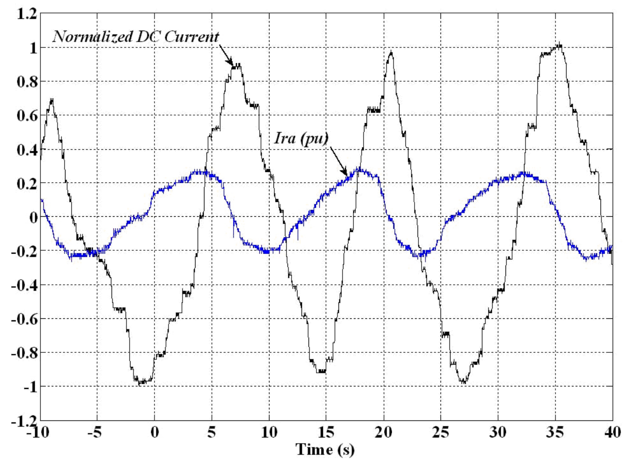


Fig. 10. Experimental results showing the periodic nature of the ξ_v.

discussed, the result in Fig. 13 shows that the value of ξ_v saturates to ± 1during a fault. In Fig. 13, the value of ξ_v is not saturated due to the appearance of the diode current.

Comparing the two methods under this condition, the value of ξ_v is still far from the threshold of 0.65, whereas the value of γ_v is very close to the threshold of 0.45. This might result in no alarm if the value of γ_v becames less than the threshold.

B. Experimental Results

The experimental setup for validating the proposed fault diagnostic technique is shown in Fig. 14. A 7.5 kW wound rotor induction generator is used as a DG and is coupled with a 7.5 kW dc motor. For safety reasons, the back to back converter is interfaced between the rotor and the utility grid. It should be noted that the proposed technique can be applied to other ac to dc converters for microgrid applications. A TMS320F2812 DSP is used to control both the rectifier and the inverter including the speed control of the dc motor and the proposed fault diagnostic system. As can be seen, only a DSP is utilized, which is why the computation time of the fault diagnostic process needs to be fast. The proposed diagnostic technique requires only few lines of firmware code compared to the methods proposed by [6], [15].

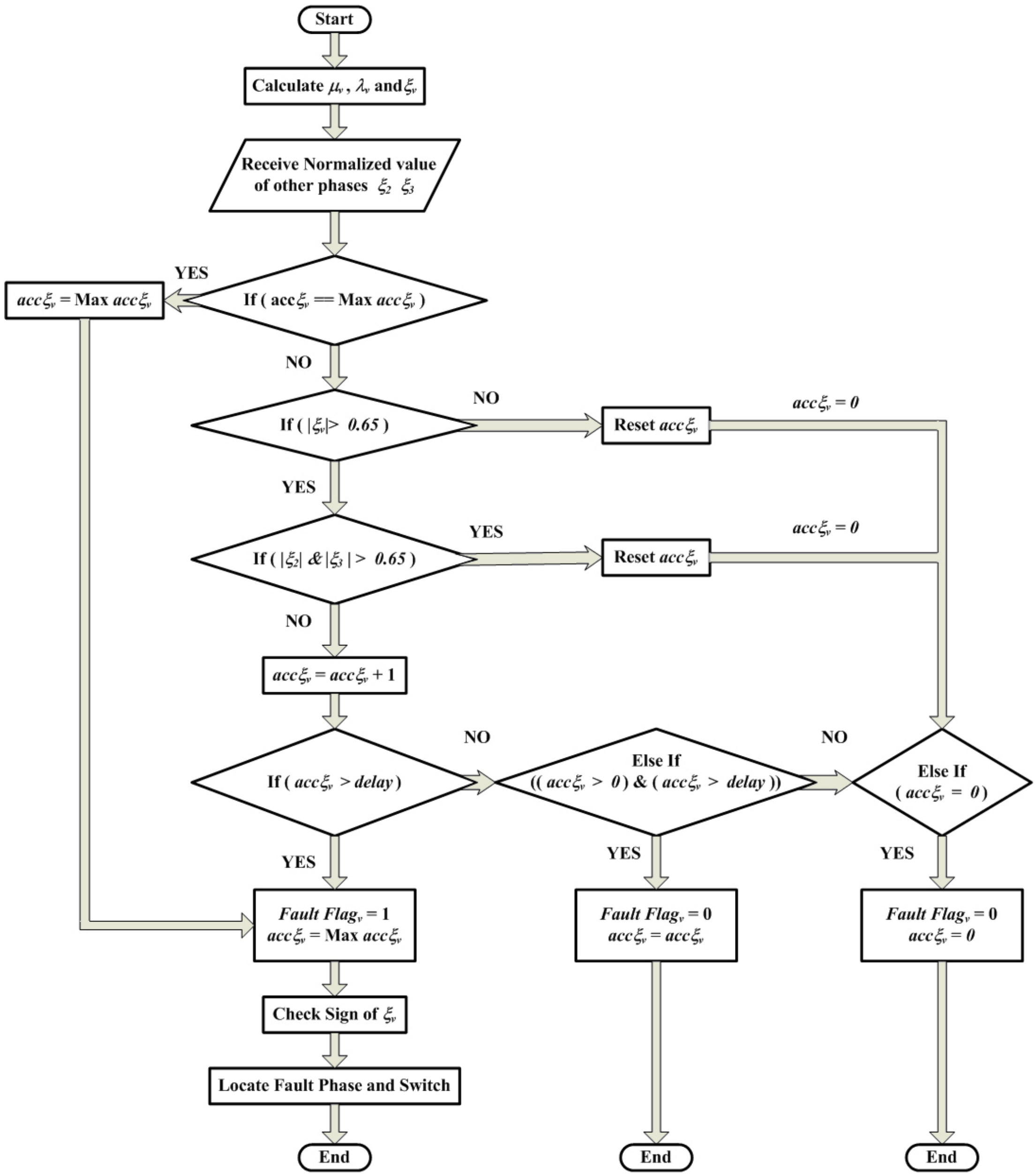
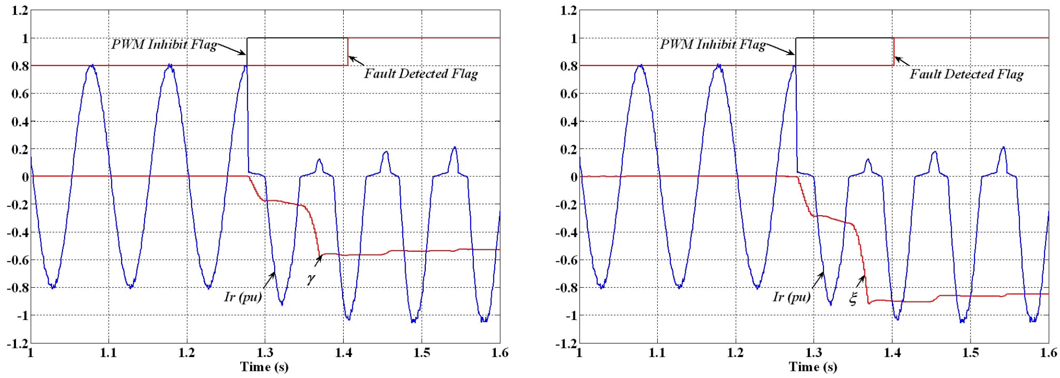


Fig. 11. The flowchart representing the algorithm used for the absolute normalized dc current method.

The experimental results shown in Figs. 15 and 16 are a comparison of the fault detection performance between the modified normalized dc current method and the proposed absolute normalized dc current method. In Fig. 15 the induction generator was operating at 10 Hz, while it was running at 50 Hz in Fig. 16.

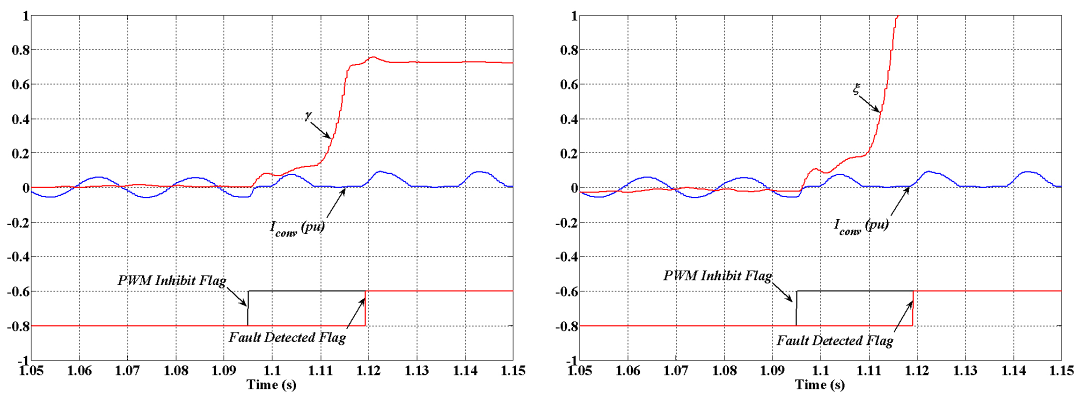
Clearly, the proposed fault detection method can perform without dependence on the frequency. This is necessary for microgrid application because DGs and RESs may operate at different frequencies. As a result, a rectifier is required to keep the dc link voltage constant. Although a fault might occur, two phase leg operation can be performed as explained in [7]. The fault detection time was about 0.125 second for 10 Hz operation and 0.025 second for 50 Hz operation.

Obviously, the proposed fault diagnostic method can perform fault detection very similar to that of the modified normalized dc current method. It should be noted that the proposed fault diagnostic technique requires less DSP computational effort than the modified normalized dc current method. Also, as shown in Figs. 15 and 16, for faults that appears at the same point, the detection times are very similar to each other, meaning that the absolute normalized dc current method is a suitable replacement. As can be seen, the simulation results and the experimental results have good agreement with each other. The results suggest that the proposed diagnostic method can be implemented by adding a few lines of firmware code to the same DSP used to control both a rectifier and an inverter. Also, the proposed method can improve the reliability of an ac to dc converter interfacing with a microgrid.



(a) (b)

Fig. 12. Simulation results comparing detection of an open-switch fault in the ac to dc converter at 10Hz fundamental frequency. (a) The modified normalized dc current method. (b) The absolute normalized dc current method.



(a) (b)

Fig. 13. Simulation results comparing detection of an open-switch fault in the PWM converter under rectifier mode at 50 Hz fundamental frequency. (a) The modified normalized dc current method. (b) The absolute normalized dc current method.

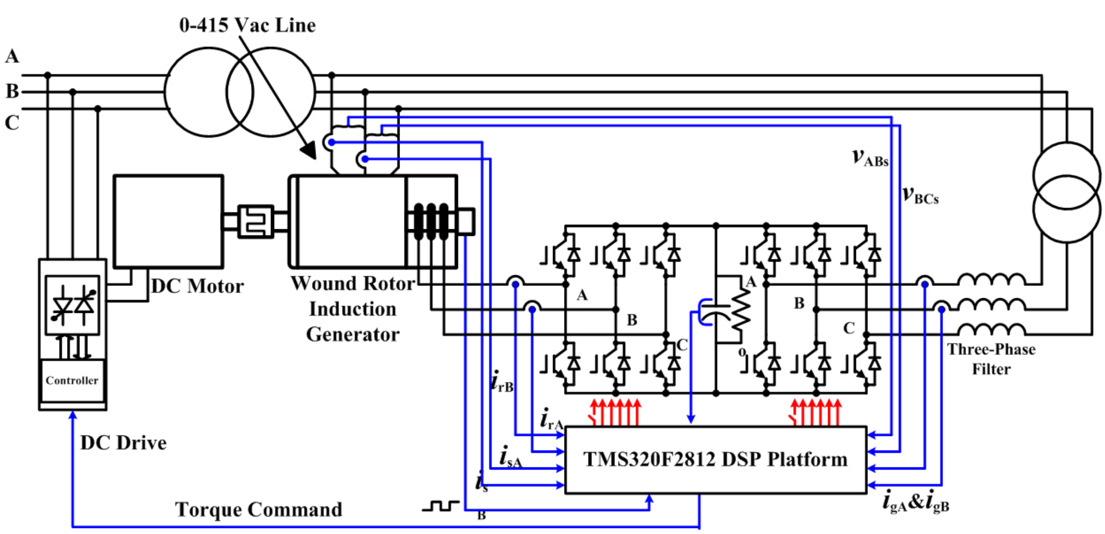
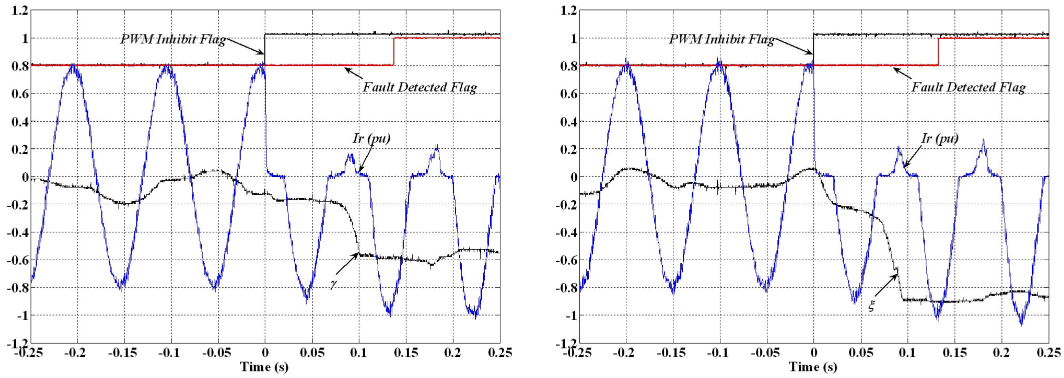
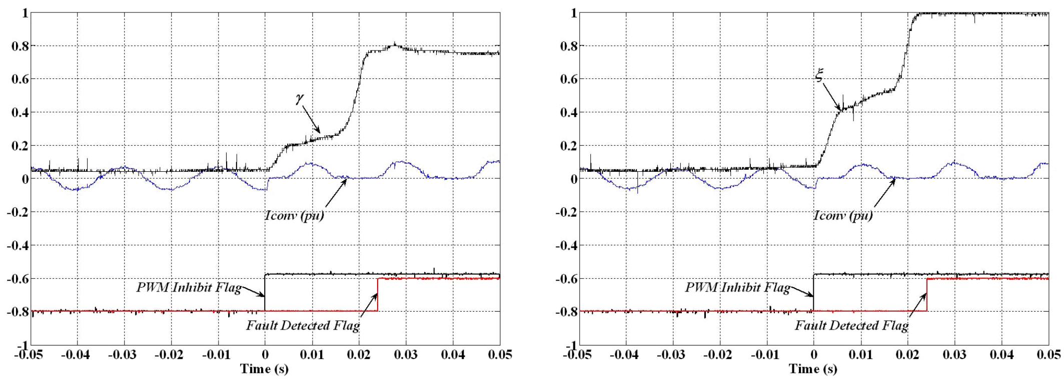


Fig. 14. Experimental setup of DFIG for the fault detection.



(a) (b)

Fig. 15. Experimental results comparing detection of an open-switch fault in the PWM converter under rectifier mode at 10 Hz fundamental frequency. (a) The modified normalized dc current method. (b) The absolute normalized dc current method.



(a) (b)

Fig. 16. Experimental results comparing detection of an open-switch fault in the PWM converter under rectifier mode at 50 Hz fundamental frequency. (a) The modified normalized dc current method. (b) The absolute normalized dc current method.

V. Conclusion

An open circuit fault diagnostic technique in IGBTs for the ac to dc converters used in microgrid applications has been developed in this paper. The proposed diagnostic method is a combination of the absolute normalized dc current method and a false alarm suppression algorithm to overcome the calculation time and fault alarm problems. The simulation and experimental results shows that the developed fault diagnostic method can detect a fault within about one cycle. The experimental results also show that the proposed fault diagnostic performs satisfactorily in detecting opne switch faults. Also, the simulation results and experimental results have good agreement with each other. The proposed diagnostic method can be implemented by adding a few lines of firmware code to the same DSP which is used to control both a rectifier and an inverter. The results illustrate that the reliability of an ac to dc converter interfacing with a microgrid can be improved by using the proposed fault diagnostic method.

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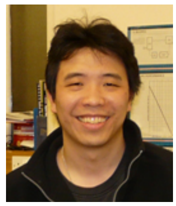

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