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Open-Transistor Fault Detection and Diagnosis Based on Current Trajectory in a Two-level Voltage Source Inverter

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Abstract

Even though technological developments in the area of control of voltage source inverter (VSI) have reached a relatively matured state, advances in improving the reliability of VSI is still a developing area. In order to improve safety as well as reliable operation, an effective fault detection and diagnosis method has to be integrated along with the control of inverter-fed systems. In this paper, implementation of open-transistor fault detection and diagnosis in VSI is presented. The current trajectory of phase currents is employed to detect the fault condition and identify the faulty switch. Implementation of this method in a three-phase two-level VSI with the aid of data acquisition card and LabVIEW software is presented with the experimental result.

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Keywords: Current trajectory; Fault detection; Fault diagnosis; Open-transistor fault, Voltage source inverter.

1. Introduction

Voltage source inverters (VSI) found a wide range of applications in variable speed drives (VSD), reactive power compensation, high-voltage direct-current transmission (HVDC), railway traction, renewable energy integration, to name a few. In all these applications, the inverter serves as the key constituent; therefore, reliability and availability of the inverter plays an important role in the consistency of the overall application. A fault in an inverter actuates the

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protection systems such as fuses, relays and circuit breakers, resulting in the immediate shutdown of the operated process, which leads to a loss in terms of human resources and wastage of raw materials. In this scenario, incorporation of a fault detection and diagnosis (FDD) method ensures the monitoring, protection, safety, reliability and reduced maintenance cost and time [1]. It is reported that power semiconductor faults contribute about 38% of the faults in inverter-fed drives [2]. As the power semiconductor switches such as IGBTs, MOSFETs are the basic building blocks of inverter; any malfunctioning affects the normal operation of the inverter. Often modulation of inverter concentrates on delivering the required speed or torque demand of the load. In order to ensure isolation of fault, avoid fault propagation and restoration of the highest degree of normal operation, an effective FDD method has to be incorporated along with the control scheme [3].

Fault detection and diagnosis in VSI found its significance towards the beginning of the nineties. Many FDD methods over the years have investigated fault detection of 3-phase VSI using current trajectory tracking. In the current trajectory tracking method, Concordia transform was first applied to the three-phase currents and then the trajectories tracked by the transformed currents were plotted. For fault-free condition, the transformed currents tracked a perfect circle. For each fault, the transformed currents track a different trajectory that was used for fault diagnosis. The use of transformed currents for trajectory tracking required a better controller or processor that adds to the cost and complexity of the system. This method was found to be especially true in the cases where FDD of VSI was implemented to an existing system without changing the original firmware [4-7]. A few methods based on artificial intelligence based methods have also been introduced for the open-transistor fault detection and diagnosis. These methods utilized the fuzzy logic controller, neural network and clustering Adaptive Neural Fuzzy Inference System (C-ANFIS) for fault detection and diagnosis [9-11].

Even though a number of techniques have been introduced in the area of fault detection and diagnosis based on current trajectory, with the advances in the area of digital controllers, software tools and artificial intelligence techniques, research in this area is in continuous development. In this paper, implementation of open-transistor fault detection in a three-phase two-level VSI with the aid of data acquisition card (DAQ) and LabVIEW software is presented. This paper is organized as follows. Section 1 gives the introduction and the existing literature background and Section 2 deals with the various aspects of faults in inverters-fed systems. In Section 3, the detection and diagnosis method based on current trajectory is detailed, followed by the implementation of the fault detection and diagnosis method with the results in Section 4 and 5, respectively. Finally, conclusions are given in Section 6.

2. Fault in inverter-fed systems

Many industrial applications are employing variable speed drive (VSD) and a typical block diagram of VSD is shown in Fig. 1 (a). The major components of drive systems are electrical machine, sensors, control logic and power circuit. Majority of the applications use induction motors to drive the load. The sensors are for measuring the mechanical and electrical quantities for the purpose of monitoring, protection and control. Control logic achieves the desired load requirement based on the control input and sensed parameters. The control action is established through the power circuit by controlling the power input to the electrical machine. The power circuit consists of rectifier, DC-link and inverter. All these components of the drive systems are vulnerable to fault [12].

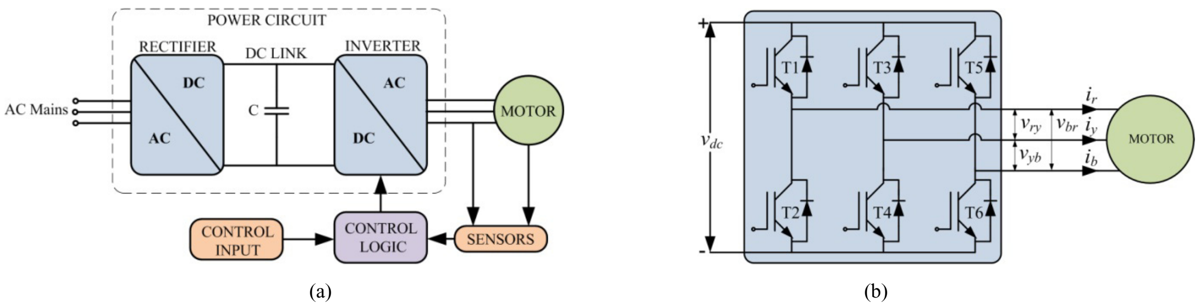


Fig. 1. (a) Block diagram of VSD; (b) Power circuit of V three-phase two-level VSI.

The possible machine faults are bearing damage, shaft misalignment, resonance, eccentric rotor, etc. Similarly, electrical faults may be due to insulation degradation, open winding, rotor bar faults, etc. [13]. Fault associated with the sensor are also critical as the control action is based on the sensed parameters that may lead to loss of control over the operated process. The fault susceptibility of control logic is very low, as it is integrated on digital platforms. The power circuit consists of a rectifier, DC link and inverter and the fault can be on any of these parts. In this paper, inverter power semiconductor fault is considered. The power circuit of VSI is as shown in Fig. 1 (b), consisting of six power semiconductor switches; three upper leg switches (T1, T3, T5) and three lower leg switches (T2, T4, T6). The power flow through the inverter is controlled by the turn-on and turn-off these switches. As far as the inverter is concerned, the fault occurs due to the disturbance in AC line side, high start-up stresses, high inrush current, DC-link capacitor voltage swing or unbalance, fault on the load side, gate driver failure, etc. [3].

The power semiconductor switch fault can be either open circuit or switch short circuit fault. The open circuit fault includes open-transistor, open-freewheeling diode and open-switch fault. In this paper open-transistor fault detection and diagnosis is presented. This fault may happen due to the loss of gate pulse or internal rupture due to overheating or external connection discontinuity resulting in degraded power output, increased harmonic content and unbalance in output. However, it does not lead to the shutdown of the system, but can remain undetected. This may cause fault propagation leading to faults in the associated components, resulting in the total system shutdown and higher maintenance costs. Therefore, open-transistor FDD is very important in the aspect of protection as well as for the implementation of fault tolerant operation to improve reliability of the total system [14].

3. Fault detection and diagnosis based on current trajectory

An integrated fault management system incorporates actions such as protection, fault detection, diagnosis, reconfiguration, fault tolerant operation, etc. General fault detection and diagnosis structure start with the sensing of system parameters such as current, voltage, speed, torque, etc. These parameters consist of fault signature under fault conditions. In order to detect and diagnose the fault, features such as current trajectory, slope of current trajectory, mean value, Fast Fourier Transform (FFT), total harmonic distortion (THD), etc. are extracted from the sensed signal and by analysing these features, presence of fault can be detected and identified. Once the presence of the fault is detected, the next step is to determine type, size, location and cause of the fault. Depending upon the severity of fault, the fault detection algorithm further decides the next step to be taken such as switch to a fail-safe state, system reconfiguration, fault tolerant operation or shut down for maintenance [15].

In this paper, output phase currents (i_r, i_y, i_b) are used for the FDD. As these currents signals are already sensed for the purpose of control of drive, this avoids the need for additional sensors for FDD. When a fault occurs, these current signatures carry the fault information, by analysing these current signatures fault can be effectively detected and identified. In this paper, the current trajectory of the phase currents is used to detect and diagnose the open-transistor fault. The current trajectory is plotted between phase current i_r and i_y. Plotting of phase current instead of direct and quadrature axes currents reduces computational requirement and complexity. Under normal operation condition, the three phase currents are purely sinusoidal and the current trajectory will be circular as shown in Fig. 2. When the load is RL or motor load, the current trajectory is elliptical in nature. Whenever a fault occurs the currents trace a particular trajectory unique for each switch and this can be used to detect the faulty switches. Different current patterns for each switch fault are depicted in Fig. 3; these current patterns are formulated based on literature and simulation. From this pattern, the faulty switch can be effectively identified, based on heuristic knowledge or pattern recognition or contour detection methods.

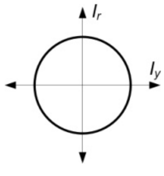


Fig. 2. Current trajectory under normal condition.

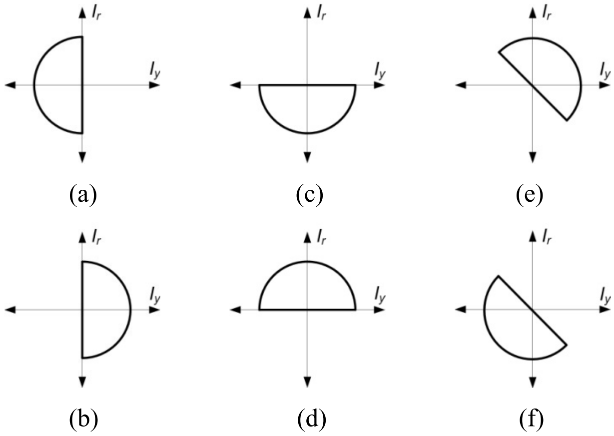


Fig. 3. Current trajectory under open-transistor fault condition.

4. Experimental setup

The fault detection and diagnosis technique based on current trajectory method has been implemented on a three-phase two-level voltage source inverter with proper gate driver circuit and a motor load in the laboratory to verify its validity. FGA15N120 IGBTs with internal anti-parallel diodes are used for the experimental setup. By maintaining a DC link voltage at 150V, sinusoidal pulse width modulation (SPWM) with a modulation index of 0.8 for a switching frequency of 1 kHz is implemented using PIC 18F4520 to modulate the VSI [16]. Using three calibrated Hall Effect current sensors, the three phase current signals are acquired to the PC through NI-6251® DAQ [17]. The fault detection and diagnosis method has been implemented in the PC using LabVIEW® software tool [18]. The block diagram and the photograph of the experimental setup are shown in Fig. 4.

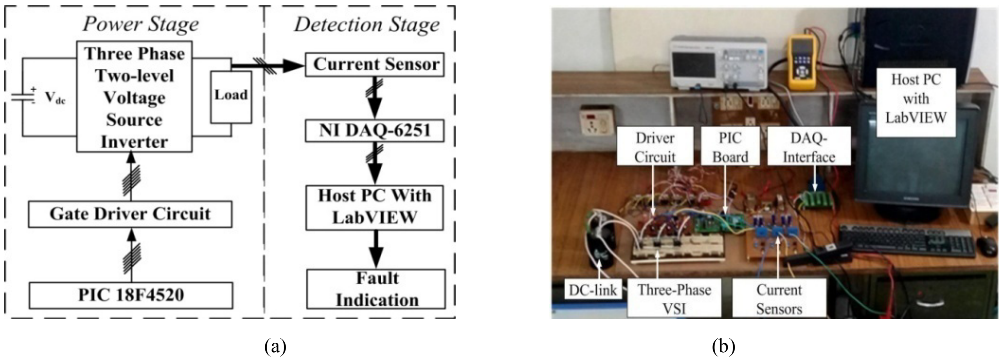
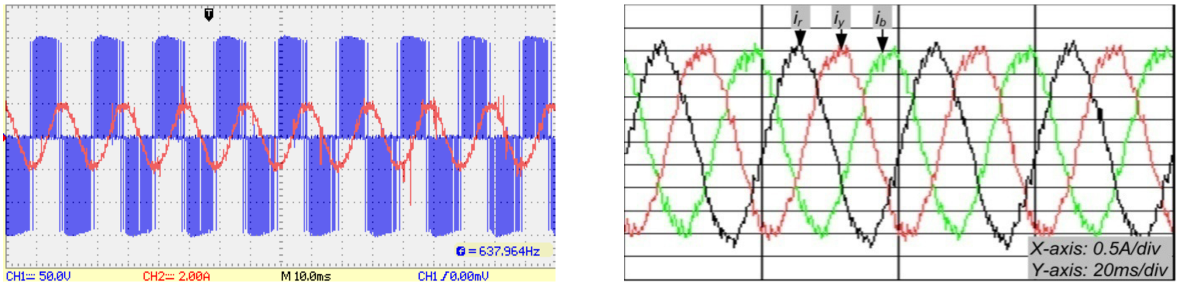


Fig. 4. (a) Block diagram; (b) photograph of experimental setup.

5. Results

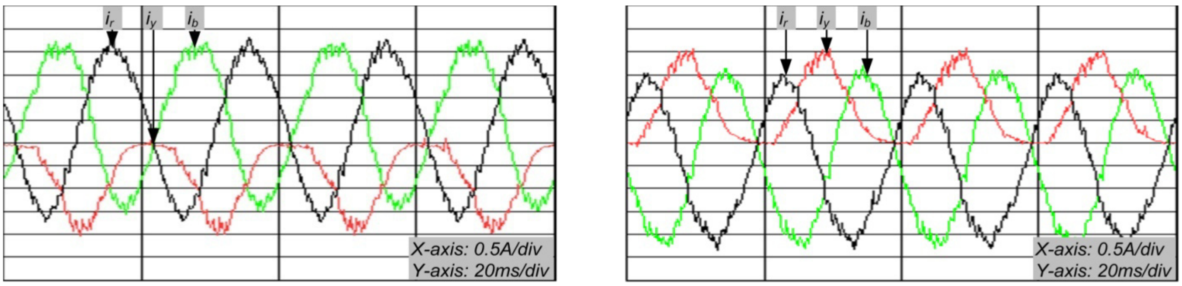
The measured waveform of the line-line voltage (v_{yb}) and phase current (i_y) and acquired three-phase current waveforms (i_r, i_y, i_b) in LabVIEW® under normal condition are shown in Fig. 5 (a) and (b), respectively. Now, the gate pulse is removed, which results in the open-transistor fault condition. The measured waveforms of the three-phase currents for the upper switch (T3) and lower switch (T4) under fault are shown in Fig. 6 (a) and (b), respectively. In this paper, results of fault on the second leg are presented, as this method works in a similar manner for the other two legs. It can be inferred that the transistor fault leads to deviation of the current waveform in the corresponding phase current. When the upper switch (T3) of the second leg is faulty, the positive half cycle of corresponding phase current (i_y) vanishes, as shown in Fig. 6 (a). Similarly, when the lower switch (T4) is faulty, the negative half cycle of phase current (i_y) vanishes, as shown in Fig. 6 (b). The other two phase currents (i_r and i_b) are also affected with unbalance during these fault conditions as shown in Fig. 6.

Now, the phase-r and phase-y currents are measured in XY-mode and the measured trajectory under normal condition is shown in Fig. 7 (a). Similarly, the acquired current signals to host PC using NI-6251® DAQ are also plotted in LabVIEW® and the plotted current trajectory under the normal operating condition is shown in Fig. 7 (b). Now, gate pulse to each of the switch is removed, which results in the open-transistor fault condition and the corresponding current trajectory for each switch are measured and plotted. The measured and plotted current trajectories under fault conditions are shown in Fig. 8 and Fig. 9, respectively.



(a) (b)

Fig. 5. Measured waveform of (a) line-line voltage (v_{yb}) and phase current (i_y) (b) three phase current in LabVIEW®.



(a) (b)

Fig. 6. Three phase current waveform (a) upper switch 'T3' (b) lower switch 'T4' under fault in LabVIEW®.

(a) (b)

Fig. 7. (a) Measured; (b) plotted current trajectory under normal condition.

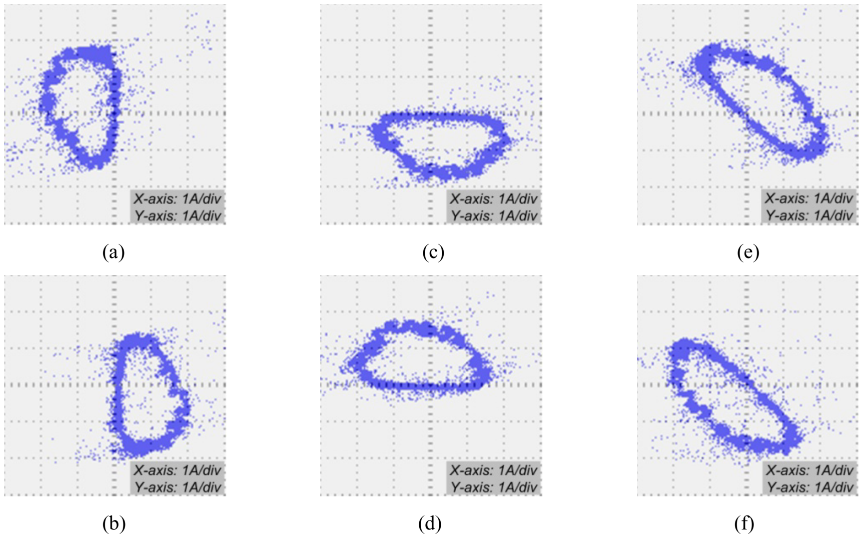


Fig. 8. Measured current trajectory corresponding to each switch under fault (a) T1; (b) T2; (c) T3; (d) T4; (e) T5; (f) T6.

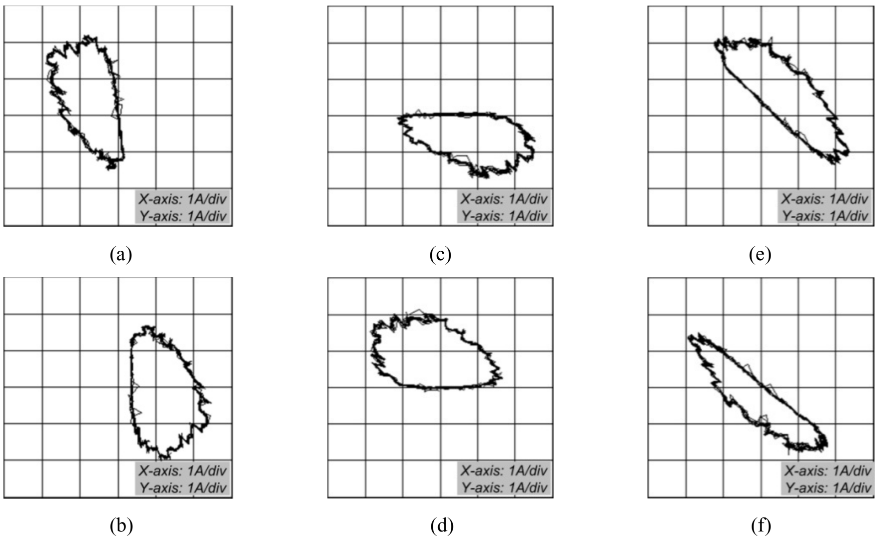


Fig. 9. Plotted current trajectory corresponding to each switch under fault (a) T1; (b) T2; (c) T3; (d) T4; (e) T5; (f) T6.

The measured and plotted current trajectories under normal shown in Fig. 7 and fault conditions shown in Fig. 8 and Fig. 9 are found to be in close agreement with the theoretical patterns shown in Fig. 3. Hence, based on the current trajectories it is possible to detect the open-transistor fault and identify the faulty switch. The current is load dependant; whenever load varies, the current patterns expand or compress in both axes. But, the patterns remain same. Therefore, this method is load independent. This can be effectively handled by normalizing the current values and plotting the current trajectories, but which adds additional stages and computational requirement. Here, the fault inference and fault localization are done based on heuristic knowledge of current pattern for literature and simulation. A simple pattern recognition algorithm or contour detection method can be implemented along with the fault detection and diagnosis to enable a user-friendly way of fault inference such that this method can be adopted in fault tolerant operations.

6. Conclusions

Open-transistor fault detection and diagnosis is vital in the aspect of protection as well as fault tolerant operation, to improve the availability and reliability of the overall system. In this paper, implementation of open-transistor fault detection and diagnosis method based on the current trajectory of phase current is presented. This method is found to be a simple, load independent method with minimum computational and implementation effort. The method has been validated by implementing it on a three-phase two-level voltage source inverter and the results prove the effectiveness of the method in detecting the open-transistor fault and identifying the faulty switch. This method can be also extended towards real-time open-transistor fault detection and diagnosis and further fault tolerant operations as well.

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