Open-Circuit Fault Diagnosis Based on the Filter Inductor Voltage for Single- and Three-Phase Inverters

Xuebing Pei[1, a]

[1]China Ship Development and Design Center, Wuhan, 430064, China

[a]email: peixbhust@163.com

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Abstract. In this paper，a new diagnostic method utilizing the voltage across the output-filter inductor as diagnostic criterion is presented for the voltage-source inverters. This voltage can be easily obtained by adding a winding across the inductor, thus the sensor is needless and the diagnostic system is naturally isolated from the inverter. The average of the absolute voltage criterion in one period can be utilized to detect the open-circuit. To realize the method, one simple analog circuit is designed to process the voltage signal. Based on the proposed method, the diagnostic effective is independent of the loads and the cost of the diagnostic system is low. The method can be applied to both single-phase and three-phase inverter. The waveform analysis, diagnostic circuit design, and the experimental results are presented in this paper. The diagnostic method is fast, and the diagnostic system is low-cost.

Introduction

The voltage-source inverters are widely utilized in the applications such as photovoltaic, small wind power, UPS, dynamic voltage restores, low power drives, etc [1]. The reliability of the inverter is very vital since many kinds of unexpected faults in inverter may influence the operation of the whole system. Among all the components in the inverter, switching devices are the most vulnerable. In general, faults occurring on them can be broadly categorized as short- and open-circuit faults [2]. Presently, short-circuit protection circuit integrated in the gate driver is already a standard part. However, open-circuit fault has not received so much attention yet, in spite of the fact that some methods are proposed to diagnosis the open-circuit faults in the inverters. The open-circuit fault will not necessarily causes the system shutdown and can remain undetected for an extended period. This may lead to secondary faults in the inverter or in the remaining drive components, resulting in the total system shutdown and higher repairing costs [3].

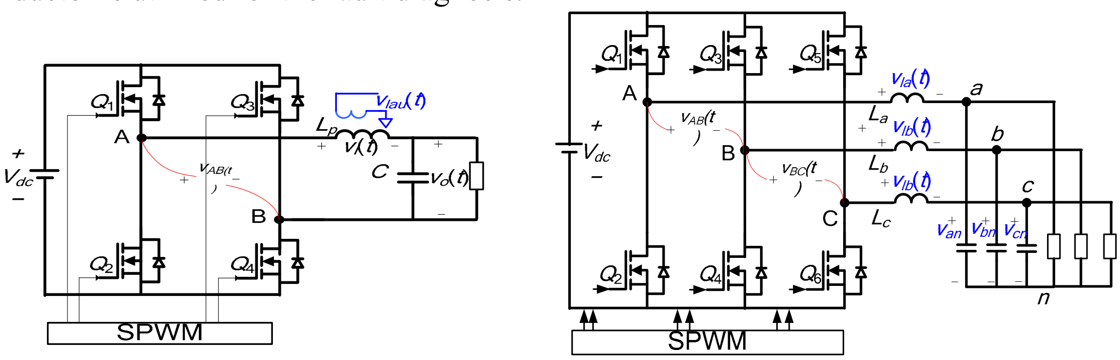
Some researches have published technical papers to address the open-circuit fault diagnosis problem for inverters [4-10]. According to the measured variables, the method can be classified into two categories: current-based methods and voltage-based methods. In [4-5], the dc-components of the load currents have been introduced as the simple carriers of the diagnostic criterions on inverter open-circuit faults. Unfortunately, the fault detection based on the dc-component tends to be highly unreliable under different operating conditions, such as light-load, fast transients. In [6], Peuget et al. introduced two methods based on the properties of the current trajectories, one is based on the slope analysis of the current-vector trajectory and the other determines the fault through the current-vector instantaneous frequency. In order to make the method independent of the load, Abramik suggested using a normalized average current instead, and thus the fundamental components of the load currents are computed by means of the DFT [7]. This method was refined in [4] and [8]. Expert systems, fuzzy logic, and artificial intelligence methods are proposed to diagnose inverter faults in [9]. However, these methods also have some drawbacks such as a higher complexity and larger detection time. Instead of using the current single as the diagnostic criterion, Ribeiro et al. [10] proposed several techniques to detect the open-circuit fault by comparing the voltage to their respective reference commands. Whereas, excessive voltage sensors can add the cost and complexity of the detections system. Q.T. An et al. [11] proposed a switching function model-based method to detect the open-circuit fault without sensors. This method is fast and low-cost but some time-delay values which must be precisely defined which can be rather difficult since they depend on many variables.

In response to these concerns, a diagnostic method for the open-circuit fault in the inverter is proposed in this paper. Unlike the traditional methods that are based on the voltage or current sensors, the proposed method uses the voltage across the output-filter inductor of the inverter as the diagnostic criterion. Since the voltage across the output-filter inductor can be easily obtained by applying an auxiliary winding across the inductor [12] or fixing a magnetic near field probe near the inductor [13], no external sensors are needed and the isolation is realized naturally. Moreover, the diagnostic method is independent of the load conditions, and the diagnostic circuit is simple and analog-circuit-based. Therefore, the whole diagnosis system could be simple, low-cost and highly reliable.

This paper is organized as follows. In Section II, the fault-diagnosis method for the open-circuit fault in the single-phase inverter is introduced first and it can be easily extended to the three-phase inverter. Based on the theory analysis, the diagnostic circuit is designed in Section III. The experimental results are shown in Section IV to verify the analysis and design. The conclusion and future work are given in section V.

Principle of Open-circuit Fault Diagnosis for The Inverter

Fig. 1 (a) shows the topology of the single- and three-phase inverters. In the single-phase inverter, the output filter voltage vl refers to the difference between the mid-point voltage vAB and the output voltage vo. Since the voltage-second value in one switching period is always zero, the average value of the filter inductor voltage is zero. This means the average value method is not suitable for the application. In this paper, the average voltage of the absolute value of the output filter inductor is utilized for the fault diagnosis.



(a)The single-phase inverter (b) The three-phase inverter

Fig.1 The topology of the inverter

A. Fault Diagnosis in Single-Phase Inverter

Fig. 2(a) shows eight switching states in the single-phase inverter under the normal condition, when the SPWM is used. The switching states can be summarized as:

The key waveforms are illustrated in Fig. 2 (b). It can be seen that the states 1-4 appear in the positive half fundamental period, and states 5-8 exist in the negative half fundamental period. Moreover, both v_{AB} and v_l are quarter-wave symmetry along the time axis.

Considering the positive half period, the average voltage of the absolute value of the output filter inductor can be written as

$$V_{ave} = 2/T \int_0^{T/2} \left| v_l(t) \right| dt = \frac{S_+ + S_-}{T/2} \tag{1}$$

where S_+ is the positive voltage-second value (the red shadow area of v_l) and S_- is negative voltage-second value (the blue shadow area of v_l).

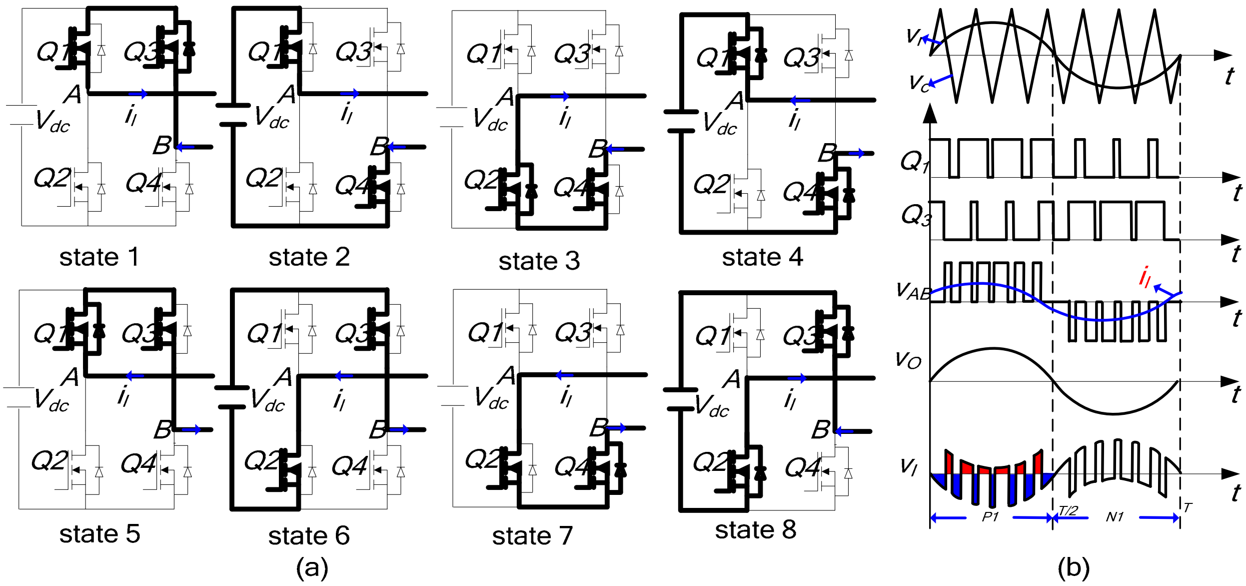


Fig. 2 The single-phase inverter under normal condition

Due to the symmetry of the single-phase inverter, only the Q_2 open-circuit fault is analyzed for the illustrative purpose. Fig. 3 presents eight switching states and key waveforms when Q_2 is under the fault. When the inductor current i_l is positive, the inverter behavior is the same as that under the normal condition (states 1, 2, 3 and 8). However, when the inductor current i_l is negative, the inverter behavior is fully different from that under the normal condition. It can be seen that the inductor current i_l is forced to the parallel diode of Q_1, instead of Q_2, as shown in states 6 and 7. Therefore, v_{AB} in the switching states 6 and 7 are 0 and V_{dc}, respectively, compared to $-V_{dc}$ and 0 under the normal condition.

It can be noticed that only the freewheeling modes (states 5 and 6) and feedback modes (state 7 and 8) exist during the negative half fundamental period, and the powering modes disappear. Because the energy transferred from load to source is very less, the states 7 and 8 can be ignored. As a result, v_{AB} is almost zero in the negative half fundamental period, and thus v_l and V_{ave} are also zero in the negative half fundamental period.

According to above analysis, it is shown that V_{ave} can be treated as the diagnostic criterion. A threshold value V_{th} can be chosen to detect the open-circuit fault. When V_{ave} is larger than V_{th}, it indicates that the single-phase inverter is under the normal condition; when V_{ave} is less than V_{th}, it shows that an open-circuit fault occurs.

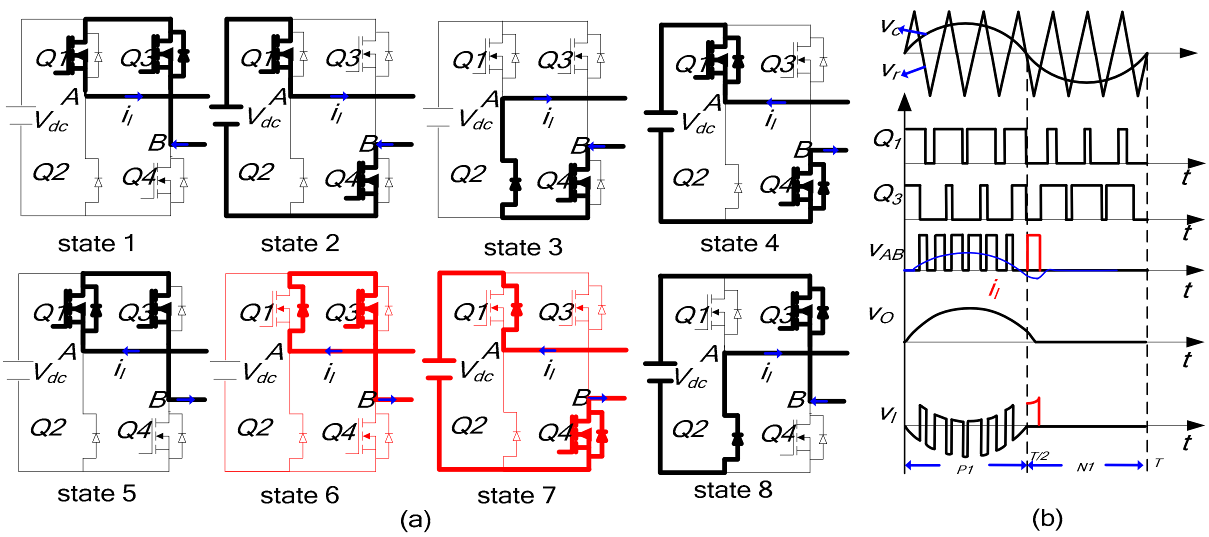


Fig. 3 The single-phase inverter under abnormal condition

B. Fault Diagnosis in Three-Phase Inverter

Fig. 1 (b) shows the topology of the three-phase inverter. According to the operational principle of three-phase inverter, the bridge mid-point voltages v_{AB}, v_{BC} and v_{CA} are mono-polar pulse, and the line voltages v_{ab}, v_{bc} and v_{ca} are sinusoid. The inductor voltages are the difference between the bridge mid-point voltages and the output line voltages. It means that the proposed method in the single-phase inverter can be also extended to the three-phase inverter. The inductor voltages are defined as

$$v_{lab} = v_{la} - v_{lb}, \qquad v_{lbc} = v_{lb} - v_{lc} \tag{2}$$

The mean absolute values of v_{lab} and v_{lbc}, named as V_x and V_y respectively, can be used to detect the state of the inverter. Under the normal condition, V_x and V_y are equivalent and can be considered as a constant. However, under the abnormal condition, the status is changed. Taking the Q_1 open-circuit fault as an example, v_{lbc} is the same as one under the normal condition, thus V_y keeps unchanged; v_{lab} reduces quickly, thus V_x is far smaller than that under the normal condition. It should be emphasized that the detected variables under the Q_2 open-circuit fault are the same as those under the Q_1 open-circuit, and therefore the proposed method can only detect the faulty leg.

Proposed Simple Fault Detection Circuit for Open-circuit Fault

From the analysis above, it's conclude that occurrence of the open-circuit can be detected by monitoring the voltage across the inductor. In our application, the voltage signal can be captured by adding an auxiliary winding in the inductor. Because of the cost limitation, a high-resolution high-bandwidth A/D converter and a floating-point processor were not used. In this paper, a simple and low-cost analog signal processing circuit is considered. Fig.4 shows the proposed circuit to diagnose the open-circuit fault of the single-phase inverter. The design of the circuit is based on the aforesaid conclusion and it consists of four sub-circuits: ABS unit, integrator unit, comparator unit and flip-latch unit.

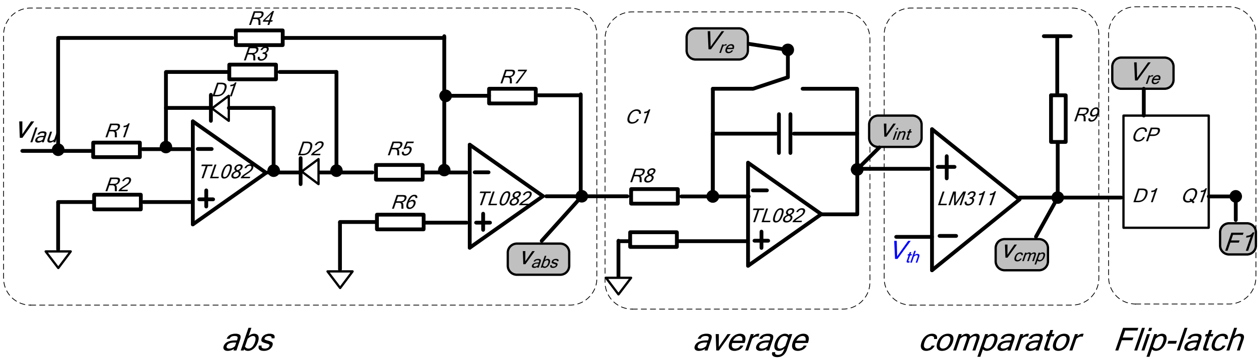


Fig. 4 The diagnostic circuit

1) ABS unit

As analyzed above, the absolute value of the measured voltage v_{lau} is utilized to fault diagnosis. Hence, a precise ABS circuit is set as shown in Fig. 4. When v_{lau} is larger than zero, the diode *D1* is blocked and *D2* is on, v_{abs} can be expressed as follows:

$$v_{abs} = \frac{R7}{R5}\frac{R3}{R1}v_{lau} - \frac{R7}{R4}v_{lau} \tag{3}$$

When v_{lau} is less than zero, *D1* is on and *D2* is blocked, vabs can be expressed as follows:

$$v_{abs} = -\frac{R7}{R4}v_{lau} \tag{4}$$

Let $R1 = R4 = R5 = R7 = \frac{1}{2}R3$, v_{abs} can be simplified as:

$$v_{abs} = \begin{cases} v_{lau}, & v_{lau} > 0 \\ -v_{lau}, & v_{lau} < 0 \end{cases} \rightarrow v_{abs} = |v_{lau}| \tag{5}$$

2) Average unit

A simple RC filter can be designed to obtain the average value. However, it will cost several periods to detect the fault. Instead, a simple integrator circuit is set. The integrate value V_{int} in one period can reflect the average value of the single $v_{abs.}$ It's noticed that a switch should be used to renew the voltage of the capacitor. The period reset signal V_{re} of the switch can be obtained easily using a NE555.

3) Comparator unit

Finally, to diagnosis the open-circuit fault, the simple logic comparator as shown in Fig. 4 is utilized. The output of the integrator circuit, V_{int} is compared to faulty reference V_{th}. When the V_{ave} is greater than V_{th}, the output of the comparator is high-level; otherwise, the output will be low-level.

4) Flip-latch unit

Once the reset signal is high, the integrate value will become zero, and the output of the comparator will be changed. In order to latch the state, the flip-latch is used to latch the output of the comparator at the rising edge of the clock signal. And the output can be kept until the next rising edge of the clock signal.

Experiment Results

To verify the possibilities of the proposed the diagnostic method, the experiments for the single-phase and three-phase inverter have been completed, and the relevant parameters are shown in Table I.

Table IElement parameters of the inverter

V_{dc}	100V
M	0.8
T	20ms
C	20uF
L_p	3.5mH

Fig. 5 shows the experimental waveforms of the single-phase inverter under the abnormal condition when the Q2 open-circuit occurs. Under the normal condition, the integrate value vint at the rising edge of Vre is larger than the threshold value, and thus the normal state is latched by the flip-latch unit and F1 keeps high-level. When the Q2 open-circuit fault occurs, vint is smaller than the threshold value, therefore, the comparator output becomes low-level, and the flip-lath unit latches the low-level at the rising edge of the Vre. As a result, F1 becomes low-level, which means the open-circuit fault occurs.

Fig. 6 presents the experimental waveforms of the three-phase inverter under the Q1 open-circuit occurring on in leg A. The diagnostic waveforms of the faulty leg are similar to those under the faulty condition in the single-phase inverter, and however, the experimental waveforms of the healthy leg are the same as those under the normal condition in the single-phase inverter. Therefore, the faulty leg can be located.

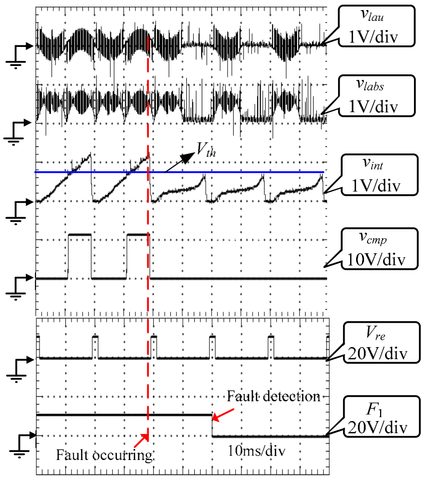


Fig. 5 Fault diagnostic waveforms in single-phase inverter

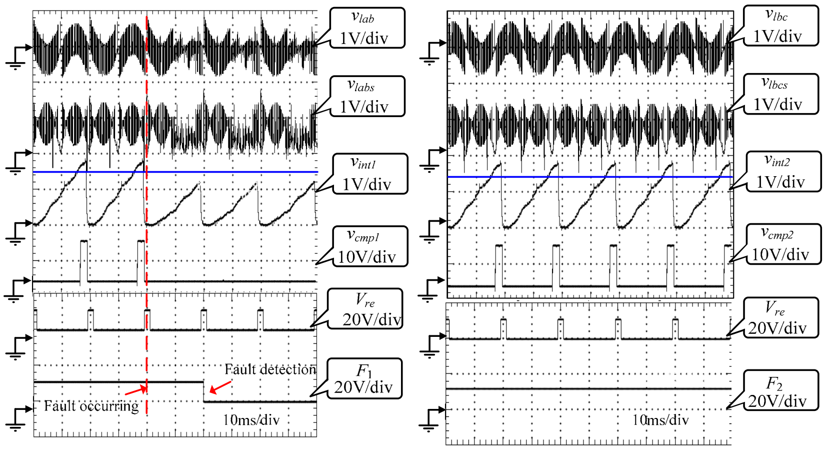


Fig. 6 Fault diagnostic waveforms in three-phase inverter

Conclusion and Future Work

This paper proposes an open-circuit fault diagnostic approach for the single- and three-phase inverters. The output filter inductor voltage is used as the diagnostic criterion. The signal can be easily obtained by adding an auxiliary winding in the filter inductor. Therefore, the external sensors are needless, and the diagnostic system is isolated naturally from the main circuit. A simple analog circuit is designed to locate the faulty switch. The fault diagnostic time is about a fundamental period. The diagnostic system is simple and low-cost.

It's noticed that the inductor voltage is the differential of the inductor current, thus the proposed method can be used to the motor-driving inverter which the current has been measured for close-loop control. Besides, based on the current and its differential (inductor voltage), the diagnostic system is more precise and the faulty switch can be also detected. This work will be done later.

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