Open-Circuit Fault Detection in Power Inverters Using Phase and Line Currents in the Time Domain

Detección de Fallas de Circuito Abierto en Inversores de Potencia Utilizando Corrientes de Fase y de Línea en el Dominio del Tiempo

Jorge A. Carrillo-Zavala[1], Eduardo Cabal-Yepez[1], Francisco J. Villalobos-Pina[2], Carlos Rodriguez-Donate[1], Ruth I. Mata-Chavez[1], Manuel J. Hernandez-Llamas[1]

[1]Departamento de Estudios Multidisciplinarios, Universidad de Guanajuato, México. ja.carrillozavala@ugto.mx, educabal@ugto.mx, c.rodriguezdonate@ugto.mx, ruth@ugto.mx, mdj.hernandezllamas@ugto.mx

[2]TecNm/Instituto Tecnológico de Aguascalientes. francisco.vp@aguascalientes.tecnm.mx

Resumen

Los inversores de potencia son componentes esenciales en los sistemas de propulsión de vehículos eléctricos, ya que convierten corriente continua (CC) en corriente alterna (CA) para alimentar motores de inducción. Una cantidad significativa de fallas ocurre en los transistores semiconductores de potencia; por lo tanto, la detección de fallas de circuito abierto en estos componentes es fundamental para prevenir un funcionamiento degradado y posibles daños a la carga. En este trabajo se utiliza un enfoque de detección de fallas basado en el análisis de las corrientes de fase y de línea mediante cálculos aritméticos simples, con el fin de evitar la necesidad de algoritmos complejos o hardware especializado. Los resultados obtenidos a partir de diferentes casos de estudio demuestran que el método empleado puede identificar con precisión las fallas de circuito abierto y las fases defectuosas en inversores sin conexión del neutro a tierra.

Abstract

Power inverters are essential components in electric vehicle propulsion systems, as they convert DC into AC to supply induction motors. A significant amount of failures occur in power semiconductor transistors; therefore, detecting open-circuit faults in these components is crucial for preventing degraded operation and potential damage to the load. In this work, a fault detection approach, based on the analysis of phase and line currents using simple arithmetic computations, is utilized to avoid the need for complex algorithms or specialized hardware. Results obtained from different cases of study, demonstrate that the employed method can accurately identify open-circuit faults and the faulty phases for inverters without a neutral-to-ground connection.

Keywords: Power inverter; Open-circuit fault; Phase current; Line current; Insulated Gate Bipolar Transistor (IGBT); Induction motor

Introduction

Power inverters are key components for electrical energy conversion and are widely used in various applications such as powering industrial motors, supplying energy to an electrical grid, converting energy from renewable sources, and in energy storage systems (Rahimpour *et al.,* 2023). In electromobility, the use of an inverter for electrical-energy conversion is essential. In electric vehicles, power inverters are a very important part of the propulsion system because they convert the direct current from a battery into alternating current to supply induction motors.

In power converters it is estimated that around 38% of failures occur in power devices (Fuchs *et al.,* 2003). A large portion of these failures take place in semiconductor elements (transistors). These failures can be either open-circuit or short-circuit (Choi *et al.,* 2015). An open-circuit fault occurs when the transistor does not conduct current, whereas a short-circuit fault occurs when the transistor does not show any resistance, allowing excessive current to flow through it. The inverter usually has overcurrent protection mechanisms (Oh *et al.,* 2015). However, when an open-circuit fault occurs, the inverter cannot easily detect it, causing the system to operate improperly and potentially leading to damage in the load (Rothenhagen & Fuchs, 2005). Based on the described above, it is important to continuously monitor the operation state of a power inverter

for determining in a timely manner when an open-circuit fault occurs and implementing the necessary corrective actions to prevent damage to the electrical systems it supplies.

Different methods have been proposed for analyzing open-circuit faults in power inverters. For instance, X. (Sun *et al.* 2023) proposed a fault diagnosis method for open-circuit faults based on signal normalization preprocessing under variable load conditions. The method uses sliding window sampling to get the acquired dataset in time. The sampled information is then processed using normalization to adjust the parameters under different loads, since tests are carried out on two motors. Subsequently, Discrete Fourier Transform (DFT) is applied to obtain signal features. Finally, the contribution graph of Principal Component Analysis (PCA) is used for locating the fault switch. Another approach is based on a mathematical model that describes possible faults, considering the DC-link voltage difference, (Yang *et al.* 2020). The model is then compared against the inverter real-time signal to detect the fault. (Wang *et al.* 2023) uses a reference voltage and compared with the actual output voltage under healthy and fault conditions. Subsequently, a Low Pass Filter (LPF) is used to avoid misdiagnosis. Then, relative β-Axis Residual Voltage is implemented to construct fault indicator, and their polarities are employed for fault location identification. Similarly, (Sun *et al.,* 2023) determined the fault through Residual Performance Evaluation (RPE). A reference model of the three-phase inverter under normal operating conditions is used, and current residuals are calculated by comparing the real output with that of the reference model. Evaluation metrics are applied to determine the presence of a fault. (Xia & Xu, 2021) consider the characteristics of an inverter to train a machine learning (ML) model by a labeled dataset, once the algorithm has been trained, an unlabeled dataset is used for implementing this approach, getting an average accuracy of 88.56%. (Kan *et al.,* 2021) combine the Discrete Wavelet Transform (DWT) with a ML model for classifying the open-circuit fault by utilizing the XGBoost algorithm, getting an accuracy of 94.12%.

The main limitations of the previously described works for open-circuit fault detection in power inverters are that most of them employ complex algorithms, demanding high computational cost by requiring specialized and expensive hardware. Additionally, some methods rely on specific parameters of the inverter being used or involve many steps which in some cases are not sufficient for accurately identifying where the open-circuit fault occurs. In the case of ML-based methods, they require a pre-training process that involves data labeling, and in some cases, signal domain transformations that increase significantly the complexity of the procedure for detecting the fault. In this work, the analysis of phase and line currents is proposed for identifying distinctive behaviors of an open-circuit fault in a power inverter, making it possible to determine in which phase the open-circuit fault occurs with high precision and effectiveness. Since this approach involves simple arithmetic operations with low computational cost, it allows using an FPGA device for its implementation to detect current variations in the time domain, without requiring complex signal processing algorithms such as those mentioned previously.

Proposed Methodology

A. Power Inverter Description:

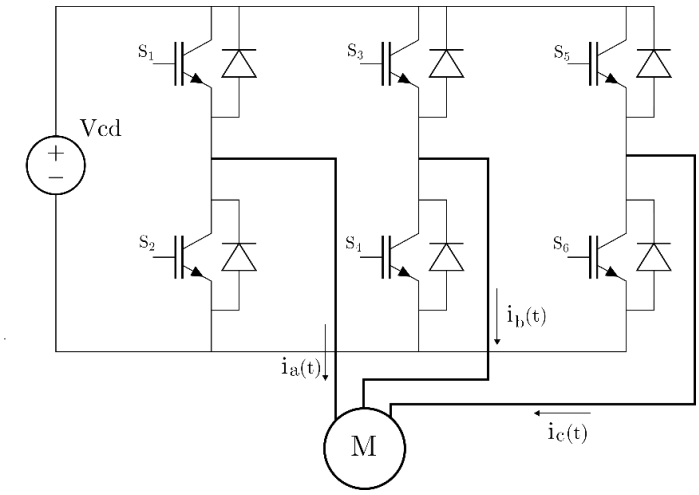


Figure 1. Three-phase power inverter feeding an induction motor. Source: Self-audit.

Figure 1 shows a three-phase inverter diagram without a neutral-to-ground connection, satisfying the condition $I_a + I_b + I_c = 0$. Open-circuit faults in power inverters occur in the Insulated Gate Bipolar Transistors (S_1, S_2, S_3, S_4, S_5, and S_6), which generate, through switching sequences, the currents feeding the different induction-motor phases. When an open-circuit fault takes place in the power inverter, asymmetric patterns appear in the phase currents (I_a, I_b, I_c) and in the line currents (I_{ba}, I_{ac}, I_{cb}), which exhibit specific features that are useful for detecting the fault. Furthermore, considering that the power inverter does not have a neutral-to-ground connection, the sum of phase currents will be always zero no matter in which switch the fault occurs. Meaning that when an open-circuit fault occurs in a specific phase current, there will be a waveform width adjustment in the remaining ones. Based on this statement, it becomes possible to detect open-circuit faults by analyzing the phase and line currents patterns through basic arithmetic operations in the time domain.

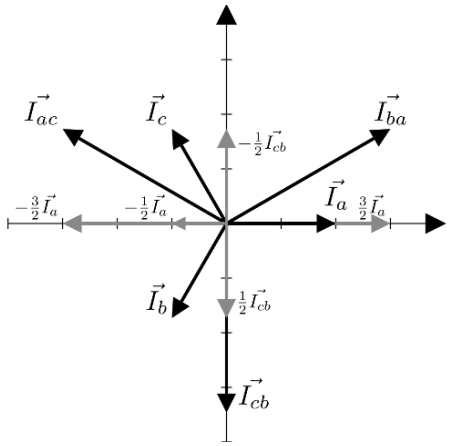


Figure 2. Reference system formed by the phase current I_a and the line current I_{cb}
Source: Self-audit.

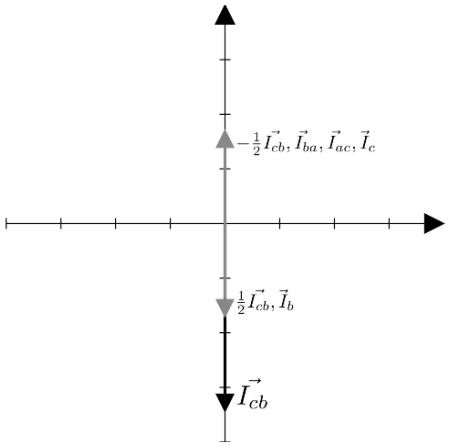


Figure 3. Rotating reference system resulting from an open-circuit fault during the positive cycle of I_a.
Source: Self-audit.

***B. Rotatory Reference System Description*:** Three rotating reference systems can be obtained from the phase and line currents of the power inverter because they are related and linearly independent. To simplify the calculations, the reference system defined by the phase current where the open-circuit fault occurs is selected. Figure 2 shows one of the three rotating reference systems that can be established. For the case analyzed in this figure, the phase current I_a and the line current I_{cb} are projected onto the remaining currents.

The following equations must be considered to detect the open-circuit fault in I_a, I_b, and I_c, respectively:

$$|\boldsymbol{I}_b|^2 = |\boldsymbol{I}_c|^2 = \left|\frac{1}{2}\boldsymbol{I}_{cb}\right|^2 \quad (1)$$

$$|\boldsymbol{I}_c|^2 = |\boldsymbol{I}_a|^2 = \left|\frac{1}{2}\boldsymbol{I}_{ac}\right|^2 \quad (2)$$

$$|\boldsymbol{I}_a|^2 = |\boldsymbol{I}_b|^2 = \left|\frac{1}{2}\boldsymbol{I}_{ba}\right|^2 \quad (3)$$

When an open-circuit fault occurs in I_a, I_b, and I_c the conditions described in (1), (2), and (3) are satisfied respectively. Therefore, phase and line currents of the three-phase inverter can be represented by a single line current factor, as shown in Figure 3. By plotting these currents, it can be observed that they become equal, which indicates the occurrence of an open-circuit fault.

To detect open-circuit faults in power inverters, a five-step methodology is proposed and implemented in software utilizing MATLAB, as shown in Figure 4. In the first step, the phase currents from a three-phase power inverter, composed of six IGBT transistors that generate the switching sequences of the phase currents, are obtained. In the second step, an instrumentation system with a control unit is used for getting the signals from the power inverter. In the third step the phase and line currents are computed using (1), (2), and (3), and their corresponding waveforms are plotted. In the fourth step, the rotating reference systems are analyzed, such as the one shown in Figure 2, to identify that one containing the phase current in which the open-circuit fault occurs. The final step consists of detecting the phase and the IGBT device where the open-circuit fault occurs.

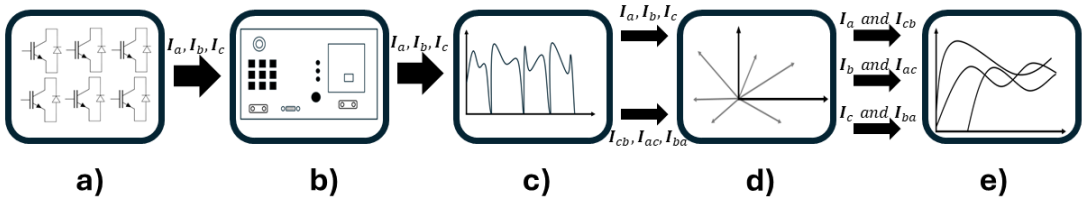


Figure 4. Block diagram of the proposed five-step methodology for open-circuit fault detection: a) Power inverter, b) Instrumentation unit and control, c) Phase and line current waveforms, d) Rotating reference system, e) Fault detection and classification. Source: Self-audit.

Results

The power inverter supplies a 12-VDC, 500-W induction motor for a light electric vehicle. For signal acquisition, a TMS320F28335 digital signal processor (DSP) from Texas Instruments is used, and the signals are sampled at a frequency of 5 kHz.

Different fault scenarios can be created by disabling specific transistors S_1, S_2, S_3, S_4, S_5, and S_6, in Figure 1 to reproduce the occurrence of an open-circuit fault. In this work, two faulty cases and one healthy case are analyzed. Figure 5 shows the patterns of the three phase currents applied to the electric motor when all the transistors operate properly.

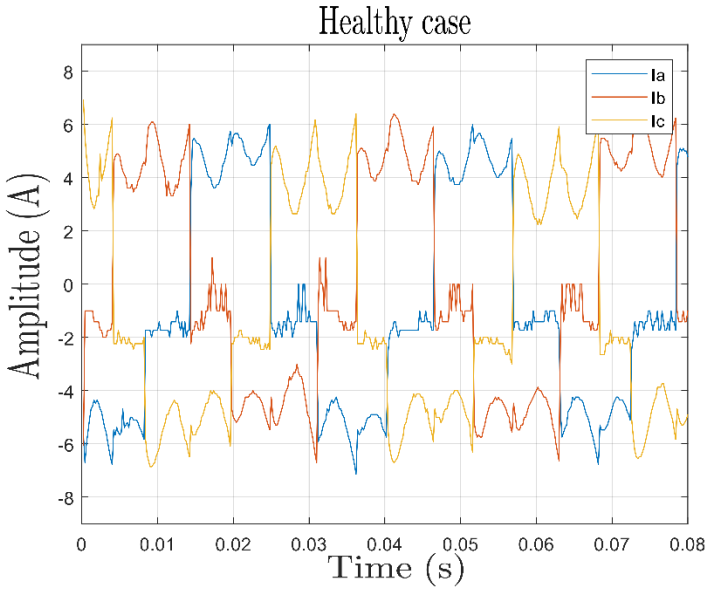


Figure 5. Healthy case phase-current patterns. Source: Self-audit.

A. Open-Circuit Fault Detection through Phase and Line Current Analysis:

The first faulty case consists of disabling transistor S_1, which controls the positive cycle of I_a, as shown in Figure 6. When the positive cycle of I_a is not present, the remaining currents adjust while maintaining the condition $I_a + I_b + I_c = 0$, which holds for any inverter without a neutral-to-ground connection.

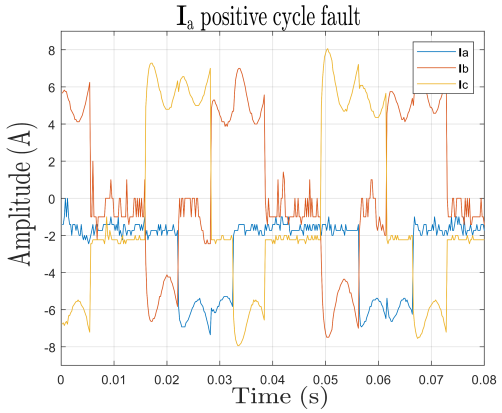


Figure 6. Current patterns when an open-circuit fault occurs in the positive cycle of I_a.
Source: Self-audit.

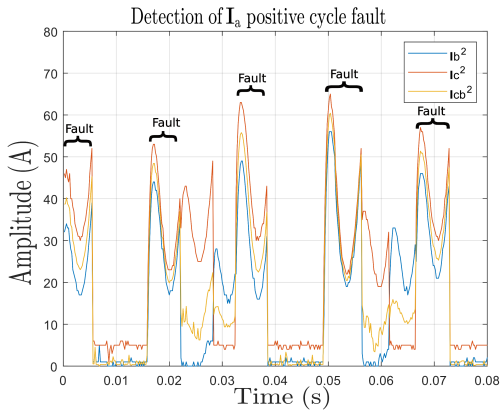


Figure 7. I_b^2, I_c^2 and I_{cb}^2 when there is an open-circuit fault in the positive cycle of I_a.
Source: Self-audit.

To calculate the currents shown in Figure 7, (1) is used. It can be observed that there are several regions where the currents I_b^2, I_c^2, and I_{cb}^2 are almost equal. This indicates that, during those intervals, an open-circuit fault occurs, for this case, in the positive cycle of I_a.

The second analyzed case consists of disabling transistors S_1 and S_4, which correspond to the positive cycle of I_a and the negative cycle of I_b, respectively. Therefore, the absence of I_a and I_b can be observed in Figure 8, while the remaining currents satisfy the condition $I_a + I_b + I_c = 0$, which holds for any inverter without a neutral-to-ground connection.

To plot Figure 9, (2) is used. As in the previous case, it can be observed that the currents become equal in certain regions; from which it can be determined that an open-circuit fault occurs in the positive cycle of I_a and the negative cycle of I_b.

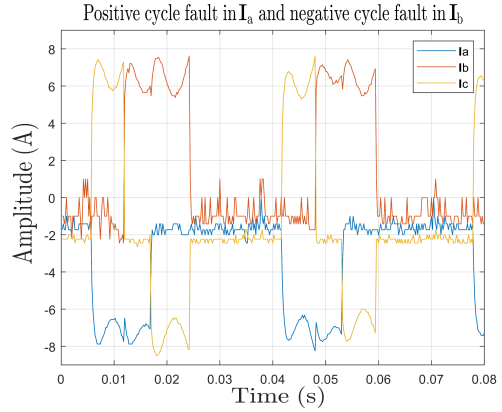


Figure 8. Current patterns when an open-circuit fault occur in the positive cycle of I_a and the negative cycle of I_b.
Source: Self-audit.

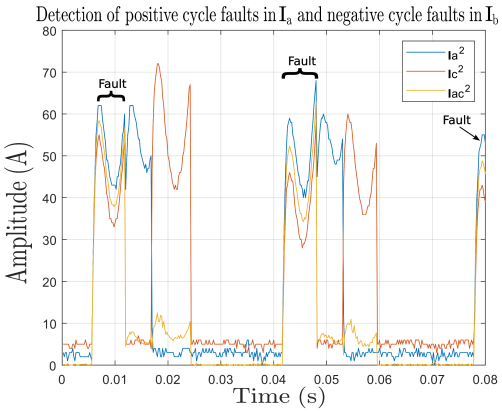


Figure 9. I_a^2, I_c^2, and I_{ac}^2 when there is an open-circuit fault in the positive cycle of I_a and the negative cycle of I_b.
Source: Self-audit.

Conclusions

This paper proposes an analysis of phase and line currents to identify distinctive behaviors of open-circuit faults in power inverters. The approach relies on simple, low-computational-cost arithmetic operations, enabling accurate and effective identification of the faulty phase. Results obtained from different case studies demonstrate that the proposed method can efficiently identify open-circuit faults when the positive cycle of $\boldsymbol{I}_a$ is not present and even when two supply phases (the positive cycle of I_a and the negative cycle of $\boldsymbol{I}_b$) fail, satisfying the condition $\boldsymbol{I}_a + \boldsymbol{I}_b + \boldsymbol{I}_c = 0$ for inverters without a neutral-to-ground connection. Future work will focus on the development of an efficient FPGA implementation for fast real-time detection of open-circuit faults in power inverters.

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