Research Article

A Sign Logic-Based Method of Current Sensor Fault Detection for PMSM Drivers

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A simplified method of current sensor fault detection and isolation (FDI) for permanent magnet synchronous motor (PMSM) drives, which only requires to collect the information of motor positions and currents of the measured phases, has been proposed in this paper. Compared with the classical state-observer-based approaches, the calculations needed in the new method only involve a few addition and logical operations. The simplicity and reliability of the new method makes itself especially useful for fault detection of current sensors in real-time control systems with limited computational capability, e.g., single-chip microcomputers (SCM) or field programmable gate arrays (FPGA). The experimental results on the basis of a FPGA controller have validated the feasibility and robustness of the proposed FDI approach.

1. Introduction

The safety in variable speed drive systems, which mainly depends on the failure-free operation of permanent magnet synchronous motor (PMSM) drives, is emphasized more and more strongly according to the requirements in practical applications. For the PMSM endowed with high dynamic performance, the vector control (or called “field-oriented control”) is the requisite function of the electric drives, using different types of sensors, e.g., DC voltage sensors, rotor position sensors, and current sensors [1]. Therefore, it is necessary to realize online fault detection of the sensors and a timely reconfiguration of the control structure to guarantee against the discontinuous operations [2].

The approaches to achieve fault detection and isolation (FDI) of current sensors can be classified into model-based [3, 4], observer-based [5, 6], and signal-based methods [7, 8]. When adopting the first two approaches, an accurate system model and a serial of parameters (e.g., resistance, inductance, and counter electromotive force), which are extremely hard to be obtained exactly, must be provided; meanwhile, a huge amount of complicated calculations are also inevitable. The above reasons make the model-

based and observer-based FDI methods difficult to gain ground in the real-time control system [2]. The signal-based FDI method proposed by Cardoso et al. [2, 9] does not claim any special demand for the system model, but the complicated integral calculations are proved to be absolutely essential. Moreover, Cardoso’s method just ensures application in an exclusive condition, where the output of the current sensor keeps zero. This paper proposed a new simplified model-free FDI method for current sensors in PMSM drives, which takes only the outputs from the current sensors and the rotor position sensors as the clues. The advantage of this method is that only a few simple addition and logical operations, rather than complicated integral calculations, are involved, which makes itself especially suitable for the real-time control systems with limited computational capability.

2. Faulty Feature Analysis

The PMSM drive adopted here consists of a DC voltage source, a three-phase voltage source inverter, a PMSM motor, and a workload (Figure 1). The inverter dominated by the field-oriented control (FOC) with three current sen-

FIGURE 1: Block diagram of the PMSM drive.

sors and a rotor position sensor is used to provide a three-phase balanced sinusoidal current to PMSM. Under healthy operating conditions, the currents of phase stators (i_{sA} , i_{sB} , i_{sC}) can be expressed by

$$\begin{cases} i_{sA} = I \cos(\omega_e t + \varphi_0), \\ i_{sB} = I \cos(\omega_e t + \varphi_0 - 2\pi/3), \\ i_{sC} = I \cos(\omega_e t + \varphi_0 + 2\pi/3), \\ \omega_e = n\omega_m, \end{cases} \quad (1)$$

where I is the amplitude of current, ω_e is the angular frequency of current, ω_m is the angular frequency rotor, n is number of pole pairs, and φ_0 is the initial phase angle of the PMSM.

If one of the three current sensors breaks down with the feedback value equaling to a random constant, a common failure mode [2], the phase shift between the other two currents will change. Taking the fault of i_{sA} as an example, the postfault currents (i'_{sA} , i'_{sB} , i'_{sC}) can be expressed by

$$\begin{cases} i'_{sA} = a, \\ i'_{sB} = I' \cos(\omega_e t + \varphi - 2\pi/3 + \varphi_B), \\ i'_{sC} = I' \cos(\omega_e t + \varphi + 2\pi/3 + \varphi_C), \\ \omega_e = n\omega_m, \end{cases} \quad (2)$$

where a is a random constant, I' is the amplitude of postfault currents, and φ_B and φ_C are the shifts of phase angles for i_{sB} and i_{sC} , respectively.

3. Principle of Fault Detection and Isolation Method

It can be inferred from eq. 1 and eq. 2 that the outputs from the two healthy current sensors (i.e., i_{sB} and i_{sC}) keep changing regularly, following the sinusoidal law, even when a fault of i_{sA} has arisen. The relationship between ω_e and ω_m also remains unchanged. To better understand the dynamics of three-phase currents, the sign of current value (SCV) was defined as follows: if the value of current is positive, the SCV returns +1, otherwise returns -1. Figure 2 shows that the step transition in each SCV curve takes place twice within a single electric cycle under nor-

FIGURE 2: Waveforms of the phase currents (i_{sA} , i_{sB} , i_{sC}) and their SCV under normal operating conditions.

mal operating conditions. If the output of one current sensor keeps constant due to the failure of normal working, the corresponding SCV curve will turn to be a horizontal line. Therefore, the fault of current sensor can be detected by monitoring the number of SCV changes within a single electric cycle, and the detailed process of fault detection for current sensor is shown in Figure 3. It can be found that the fault diagnosis based on the information from the position sensors and current sensors can be realized by extremely simple calculations, only involving several addition and logical operations. The low computational cost of the proposed FDI method makes itself especially suitable for FPGA with VHDL language.

4. Experimental Results

To evaluate the performance of the proposed sensor fault detection and isolation method, an experimental platform consisting of a PMSM and a voltage-source inverter with three-phase current sensors was established, as shown in Figure 4. A FPGA controller (model EP1C20F324 from ALTERA) was adopted for motor control utilizing the VHDL language, and the computational frequency for current closed-loop control and fault detection was initially set to 20 kHz. The control signals (C1 ~ C6) are sent to the gate drive of the three-leg inverter, which takes IR2130D (with a constant data time of 2 μ s) and IRFP240 from International Rectifiers as its main electronic devices. A 100 V DC source is used to supply power to the controller. The communication period between the FPGA controller and PC is 200us, using a point-to-point serial communication bus.

Figure 5 shows the experimental results for the case that the reference speed of PMSM reached 450 rpm, and

FIGURE 3: Flow chart of fault detection for current sensors. θ is the cumulative change of motor angle; θ_0 is the initial value of θ ; sign_n is the value of SCV; i_{sx} is the output of one current sensor; the counter_x is the number of SCV changes; fault_x is the fault indication (x represents sensor A, B, or C).

FIGURE 4: The experimental setup.

an abrupt fault was artificially exerted on the sensor A (i.e., $i_{sA} = 0.2$ A) at $t = 56.002$ s. It can be found that the three diagnostic variables all keep no less than 2 under the healthy operating mode, but the counter_A decreases to 0 at $t = 56.022$ s (nearly an electric cycle after the fault occurrence), leaving the counter_B and counter_C to keep changing in normal fashion. All this information indicates that the faulty sensor has been isolated accurately. The robustness of the proposed FDI method to speed transients was tested, employing the speed open-loop control mode. The rotational speed and direction can be altered by applying a random external load. The diagnostic variables for the three current sensors always maintain no less than 2 when the rotational speed varies at random, or even the rotational direction

FIGURE 5: Evolution of PMSM currents and fault detection variables for the case that fault occurs in sensor A.

FIGURE 6: Evolution of the motor speed and diagnostic variables under the time-varying speed conditions.

has been changed (Figure 6). Thus, it can be inferred that the variation of rotational speeds does not affect the accuracy of the new diagnosis method. Also, the robustness of the proposed FDI method to the transients in current amplitudes is presented in Figure 7, where the speed close-loop control mode was adopted with the reference speed of 150 rpm. The diagnostic variables never jump to the value below 2 irrespective of the variation of current amplitudes, indicating that the new FDI method is insensitive to the current amplitude.

FIGURE 7: Evolution of the current amplitudes and diagnostic variables under the time-varying workload conditions and constant motor speed.

5. Conclusion

A simplified on-line fault detection and isolation (FDI) method for current sensors was proposed in this paper. This method can be applied to deal with signal-loss fault mode. The fault occurrence can be identified readily and correctly by means of counting the number of SCV changes within an electric period, which mainly relies on the information of the position sensor and current sensors. The diagnostic variables reflecting the working status of current sensors will respond to the sensor fault after an electric cycle of the current controller since it occurs. The newly proposed FDI method has been tested in FPGA hardware logic elements with VHDL language, and the experimental results have illustrated the feasibility and robustness of this method.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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