An extended sensor fault tolerant control method applied to three-phase induction motor drives

Minh Chau Huu Nguyen[1,2], Cuong Dinh Tran[3]
[1]Faculty of Electrical Engineering and Computer Science, VSB-Technical University of Ostrava, Czech Republic
[2]Faculty of Electrical and Electronics Engineering, Vietnam Aviation Academy, Ho Chi Minh City, Vietnam
[3]Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

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ABSTRACT

This research presents a fault tolerant (FT) control method for three-phase induction motor drives (IMDs) against sensor failures in the operating process. In this paper, an IMD applied the field oriented (FO) control for the speed and torque control is used to study the operation under sensor fault conditions. A fault detection isolation function is integrated into the FO control loop as an intermediary component to evaluate the quality of the measured signals of the sensors and provide proper signals for speed control of the drive system. A combined method of a comparison algorithm and a third difference operator (TDO) is proposed for the fault diagnosis function to improve the sustainable operation of the drive. The reliability of the proposed method will be verified through the operation mechanism of the FT function corresponding to three sensor fault states and a random noise state in the simulation environment by MATLAB/Simulink software.

Corresponding Author:

Cuong Dinh Tran
Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering
Ton Duc Thang University
19 Nguyen Huu Tho, District 7, Ho Chi Minh City, Vietnam
Email: trandinhcuong@tdtu.edu.vn

1. INTRODUCTION

As a companion to the continuous development of advanced inverter technology, the three-phase induction motor drive (3~IMD) systems captured an increasingly more comprehensive market share for control applications in speed control, such as crushers, cranes, and elevators [1], [2]. Two main group methods for precise speed control based on switching pulse control of inverter systems in IMD include scalar control and vector control (VC) [3], [4]. With more outstanding advantages, the VC group is an example of the speed control method in a wide range; this group includes two main ways: direct torque (DT) control and field oriented (FO) control. The FO control method, which can accurately control speed and torque, is often applied in high-performance applications [5], [6]. The 3~IMD studied in this paper works based on the FO method for motor speed control.

The sensors provide the measured signals, including stator currents and rotor speed, to the FO control loop based on the independence of rotor flux and torque to control motor speed. Consequently, the performance and success in the motor drive operation based on the FO control technique will depend crucially on the accuracy of the sensor feedback signals [7], [8]. Therefore, to ensure the stable operation of the motor drive system, any failures that occur with the feedback signals should be evaluated and solved accordingly; this processing is called the fault tolerant (FT) control technique. Due to the increasing requirements for IMD systems' safety, reliability, and maintainability, integrating FT control function into the control process has been considered an essential requirement enormously recently [9], [10]. The FT function consists of two core processes: the sensor fault diagnostic and the reconfiguration. The fault diagnosis step will check the quality of the measured signal from the sensor and evaluate whether a sensor fault has occurred, thereby providing a fault warning indication for a particular sensor and starting the reconfiguration process in the event of a failure.

A typical FO speed control IMD system, for optimum size and economy, consists of two (or three) current sensors integrated into the converter and an encoder mounted on the rotor shaft. Therefore, sensor fault diagnosis techniques will focus on evaluating the quality of the signals in the operation of these two sensor types. Depending on the research objective, diagnosis methods may focus on detecting the fault of only one type of sensor or both. Corresponding to the failure state in the speed sensor, most of the fault diagnostics methods rely on the abnormal deviation between measured signals from the encoder and virtual signals from filters such as Luenberger observer [11], Kalman filter [12], and model reference adaptive system (MRAS) estimator [13] to detect a malfunction. According to the number of sensors in IMD, studying current fault diagnosis methods can apply many techniques to reach a proper approach [14], [15]. According to an IMD using three current sensors, the most effective diagnostic way is based on Kirchhoff's current law to detect sensor failures [16], [17]. However, Kirchhoff's law should not apply to check current sensor faults in the case of an IMD using only two current sensors. Therefore, other approaches are studied to determine the status of the current sensor, such as using abnormal deviations in the assessment algorithms [18], [19], the odd change of the current signal [20], [21], and the complex combination algorithm [22]. After the fault diagnosis process determines that the sensor signal problem has occurred, reconfiguration is triggered to use the proper estimated signals supplied to the FO control loop instead of the measurement signals. All appropriate sensorless techniques can be applied to provide an estimated signal for the IMD FO control method, such as neural network [23], MRAS [24], [25], and sliding mode observer (SMO) [26], for the estimated speed, or direct estimators [27], [28], Luenberger observer [29], [30], for virtual currents.

The premise of the diagnostic methods based on the comparison between measured and estimated signals is that the estimated signal must be accurate; however, this sensor type's estimated signal is generated by another sensor type's measured signal. Therefore, these diagnosis methods can misdiagnose the type of sensor failure, leading to inappropriate fault detection isolation (FDI) unit decisions. In contrast, fault diagnosis methods based on changing the measured signals are susceptible, leading to misdiagnosis with random noises.

A proposal on a diagnosis technique to solve the above weakness by combining the dipper throated optimization (DTO) and the comparison algorithm for sensor fault determination is present in this paper. The proposed method operates correctly with each type of sensor fault and avoids misidentification with random noises. That means the FDI unit will display fault indication for sensor faults, and the IMD system will be switched to sensorless mode. The outstanding advantage of this solution is that the FDI function will not recognize the fault for random noises occurring quickly and still work in sensor mode. The feasibility and effectiveness of the technique will be verified through the operation mechanism of the FT function according to three sensor fault states and a random noise state in the simulation environment.

2. PROPOSED FAULT TOLERANT CONTROL METHOD

This section describes the mathematical model of a 3~IMD and a model integrated IMD with the proposed FT function against sensor failures. The mathematical model for the induction motor (IM) is presented in the form of the state equations of the current and flux variables in the first sub-section. The second sub-section focuses on the sensor fault diagnosis algorithm for the FT control method. This proposed sensor fault diagnosis algorithm will combine the third-difference operator (TDO) technique and signal comparison algorithm to determine the sensor fault conditions.

2.1. The mathematical model of the three-phase induction motor

This paper uses the FO technique to control the IMD's precise motor speed and electric torque. IMD systems consist of main parts: the controller, the inverter, and the motor connected to the operating load. The typical structure of a motor drive is shown as a block diagram in Figure 1. The relationship between electrical quantities in IM, such as current, voltage, and speed, is nonlinear. These equations are represented in the [αβ] coordinate system as the state equations. The system of state variable equations in the machine model is presented in (1):

$$\dot{X} = \Gamma X + HU \tag{1}$$

Where: $X = [i_\alpha, i_\beta, \psi_{R\alpha}, \psi_{R\beta}]^T, U = [u_\alpha, u_\beta]$;

$$\Gamma = \begin{bmatrix} -\Gamma_1 & 0 & \Gamma_2 & \Gamma_3\omega_r \\ 0 & -\Gamma_1 & -\Gamma_3\omega_r & \Gamma_2 \\ \Gamma_4 & 0 & -\Gamma_5 & -\omega_r \\ 0 & \Gamma_4 & \omega_r & -\Gamma_5 \end{bmatrix}, H = \begin{bmatrix} \Gamma_6 & 0 & 0 & 0 \\ 0 & \Gamma_6 & 0 & 0 \end{bmatrix}^T;$$

$$\Gamma_1 = \frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2}, \Gamma_2 = \frac{L_m R_r}{\sigma L_s L_r^2}, \Gamma_3 = \frac{L_m}{\sigma L_s L_r}, \Gamma_4 = \frac{L_m R_r}{L_r}, \Gamma_5 = \frac{R_r}{L_r}, \Gamma_6 = \frac{1}{\sigma L_s}, \sigma = 1 - \frac{L_m^2}{L_s L_r};$$

Where $\omega_r = p\omega_m$, ω_r is rotor speed, ω_m is mechanical speed, and p is number of pole pairs.

The stator currents are converted to the [αβ] coordinate using the Clark formulas to perform control and estimation tasks. Then, due to the control characteristics of the FO algorithm, the currents in the coordinate [αβ] will continue to be converted to the rotation coordinate [xy] by the park formula system. The Clark and Park transformation matrix in (2) and (3):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_x \\ i_y \end{bmatrix} = \begin{bmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Where "γ" is rotor flux angular, the "i_x" component is applied to adjust the rotor flux, and the "i_y" component is used in the torque control of the IM.

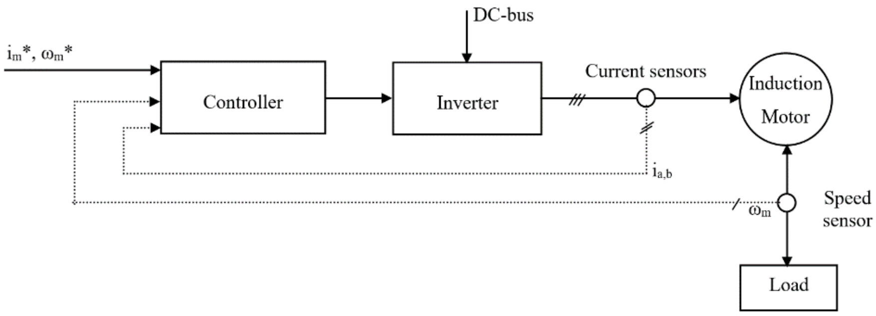

Figure 1. 3~IMD based on the FO control method

2.2. The fault tolerant control technique applied to three-phase induction motor drive

The 3~IMD based on the FO technique with an integrated FDI unit to perform the FT function against sensor faults is illustrated as shown in Figures 2 and 3. During operation, the sensors' measured current and speed signals will be transferred to the FDI unit to evaluate the signal quality. The estimators use the appropriate sensorless techniques to create virtual signals for the diagnosis and reconfiguration processes.

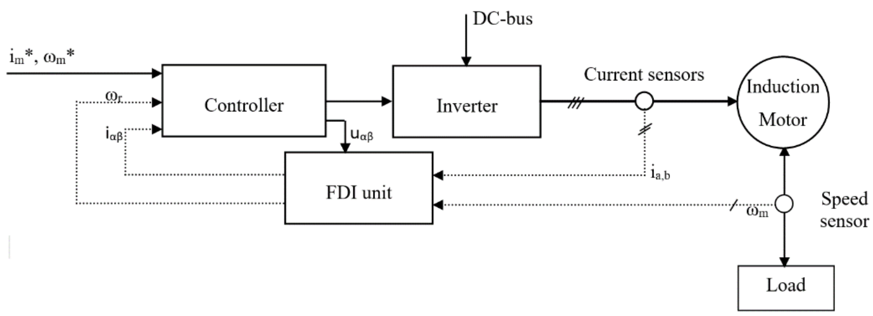

Figure 2. The 3~IMD based on the FO control method with an integrated FDI unit

Based on the measured and virtual signals, the FDI unit will conduct diagnostics on the operation status of the sensors. If the sensor condition is healthy, the FDI unit will provide a measurement signal to the

FO control loop; otherwise, the faulty measured signals are replaced with the estimated signs. The diagnostic phase based on the TDO technique is checked first to identify the abnormality of the measured signals, including speed and current signals, as in (4)-(6):

$$TDO_{jm} = \left|\Delta^3 i_{jm}(k)\right|; \tag{4}$$

$$If(TDO_{jm} >= Thj)\{F_{TDOjm} = 1;\} \tag{5}$$

$$\begin{cases} 3^{rd} \text{ operator: } \Delta^3 i_{jm}(k) = \Delta^2 i_{jm}(k) - \Delta^2 i_{jm}(k-1) \\ 2^{nd} \text{ operator: } \Delta^2 i_{jm}(k) = \Delta^1 i_{jm}(k) - \Delta^1 i_{jm}(k-1) \\ 1^{st} \text{ operator: } \Delta^1 i_{jm}(k) = i_{jm}(k) - i_{jm}(k-1) \end{cases} \tag{6}$$

Where "j_m" is measured signals, such as "i_a, i_b, ω_m"; (k) is the present sampling time; $(k$-1) is the previous time. The threshold "Thj" is selected higher than the index values corresponding to normal operating conditions. Referring to references and checked by simulations, the thresholds should be 0.5 A with the current indexes and 10% corresponding to the reference speed.

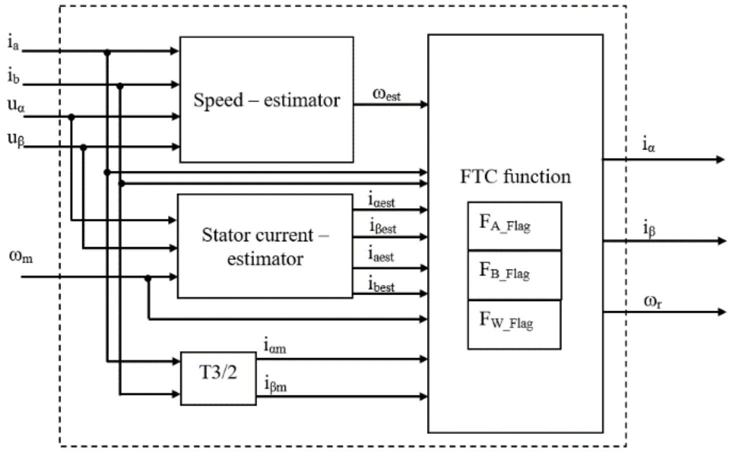

Figure 3. The structure of the FDI unit

After detecting the abnormality of the measured signal, a comparison algorithm will be carried out to accurately determine the sensor faults or random noise, as in (7) and (8):

$$\begin{aligned} &If(|j_m - j_{est}| > Thj)\{F_{COMj} = 1;\} \\ &Else\{F_{COMj} = 0;\} \end{aligned} \tag{7}$$

$$\begin{aligned} &If((F_{TDOjm} \&\& F_{COMj}) = 1)\{F_j = 1;\} \\ &Else\{F_j = 0;\} \end{aligned} \tag{8}$$

Where "j_{est}" is measured signals, such as "i_{aest}, i_{best}, ω_{est},"; "F_j" is the fault indicator corresponding to each of the sensors. According to the fault indicators, the FDI system provides the measured signs to the FO controller if the fault indicators are at a low level. Otherwise, if the fault indicators are at a high level, the FDI system provides the corresponding virtual signs to keep the operation of IMD in stable conditions. The principle of the FDI unit is shown in Table 1.

Table 1. The indicators of the FDI unit

Indication flag	Sensor status	Outputs
F_w=0, F_A=0, F_B=0	Normal	ω_m, i_α, i_β
F_w=1, F_A=0, F_B=0	Speed fault	ω_{est}, i_α, i_β
F_w=0, F_A=1, F_B=0	Faults in A-phase	ω_m, $i_{\alpha est}$, $i_{\beta est}$
F_w=0, F_A=0, F_B=1	Faults in B-phase	ω_m, $i_{\alpha est}$, $i_{\beta est}$

Remark: any appropriate sensorless method with high accuracy can be used to provide a virtual speed signal, such as neural networks [23], MRAS [24], [25], and SMO [26], and virtual currents, such as direct estimation technique [27], [28], and Luenberger observer [29], [30].

3. RESULTS AND DISCUSSION

In this part, four simulations, including three sensor failures and random noise, are performed to test the competence of the proposed FT control method. The IM model (2 pole pairs) used for simulations has the machine parameters, as in Table 2. The reference value of the motor speed for IMD is kept at zero for 0.5 seconds and then raised to 750 rpm, corresponding to 50 percent of the rated speed, as shown in Figure 4. Four cases are simulated in sequence, including open circuit faults, scaling faults of the current sensor, the speed sensor's open circuit fault, and the random noise case of the speed sensor. The FT function must detect the fault for the three sensor failure cases and replace the false signs with an estimated sign. During speed control, random noise of feedback signals (mainly caused by data reading fault or bit overflow in a short time) often occurs and has almost no effect on the operation of the IMD; therefore, the FT function should not misdiagnose the noises with sensor faults.

Table 2. The motor parameter

Description	Value
Rated torque	14.8 Nm
Rated motor speed	1420 rpm
Rated stator current	4.85 A
Stator/rotor resistance	3.179/2.118 Ω
Magnetizing inductance	0.192 H
Stator/rotor inductance	0.209/0.209 H

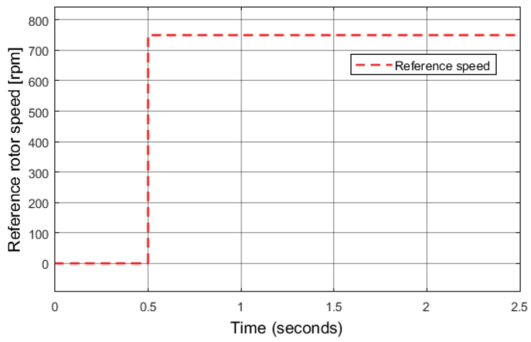

Figure 4. Reference speed

In the first case, the IMD operates in normal conditions according to the reference speed; at 1.5 sec, an open circuit problem occurs with the A-phase current sensor, causing the feedback current to be zero (Figure 5(a)). The FDI unit's FT control function immediately detects the feedback signal's abnormal failure from the A-phase current sensor. It triggers the corresponding fault indicator to go high (Figure 5(b)). According to the fault indicator, the FDI unit will use the virtual currents to replace the stator current for supply to the FO control loop (Figure 5(c)). As a result, the IMD maintains regular operation even under an open circuit current sensor fault condition (Figure 5(d)).

In the second case, a scaling fault occurs with the B-phase current sensor, causing the measured current to be triple (Figure 6(a)). The FDI unit detects the abnormal fault of the signal from the B-phase current and triggers the corresponding fault indicator to go high (Figure 6(b)). Similar to the first case, the virtual currents replace the measured current for supply to the controller (Figure 6(c)), and the IMD still maintains regular operation even under fault conditions (Figure 6(d)).

In the third case, an open circuit fault occurs with the speed sensor at 1.5 sec, and the measured speed value becomes zero (Figure 7(a)). The proposed FDI function has proven its effectiveness when accurately diagnosing the failure of the speed sensor. The speed sensor fault indicator is raised to a high level while the two current fault indications remain low (Figure 7(b)). According to the speed sensor fault indicator, the FDI unit used the estimated speed to supply the FO control control loop (Figure 7(c)). The IMD still operates stably under an open circuit speed sensor fault condition, shown as the actual speed in Figure 7(a).

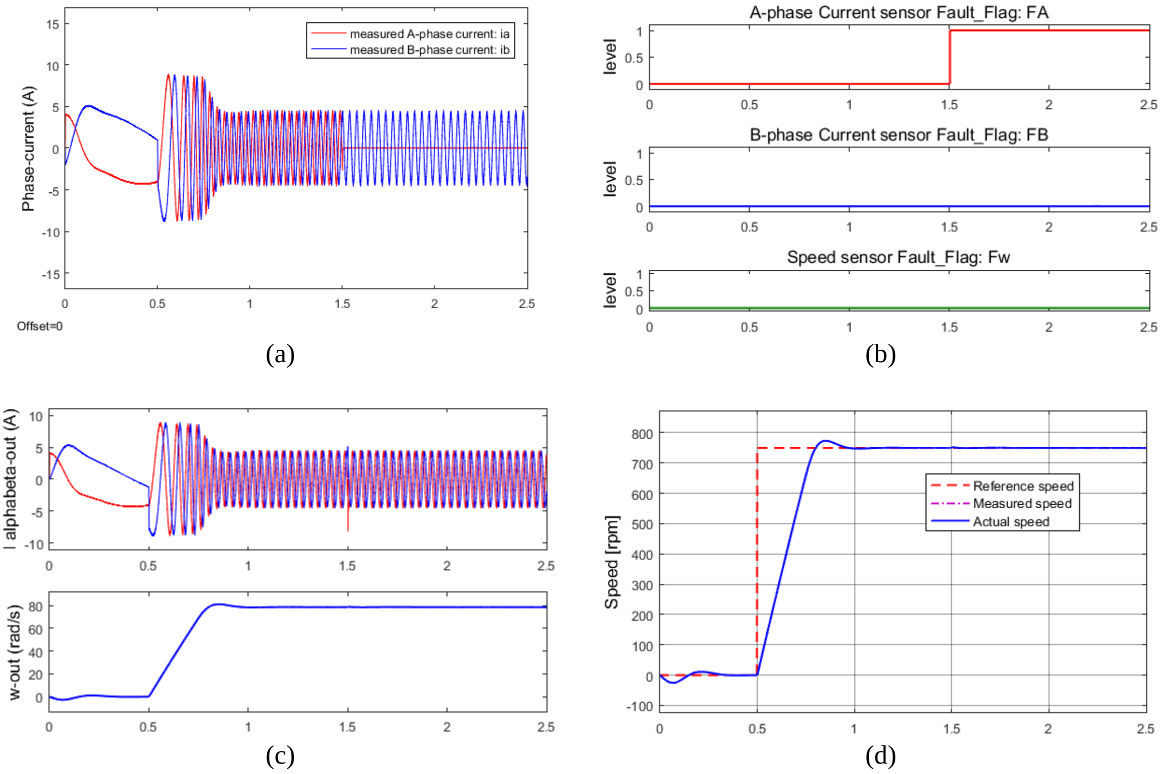

Figure 5. Open circuit fault at A-phase sensor: (a) measured currents, (b) indicators, (c) outputs of FDI, and (d) motor speeds

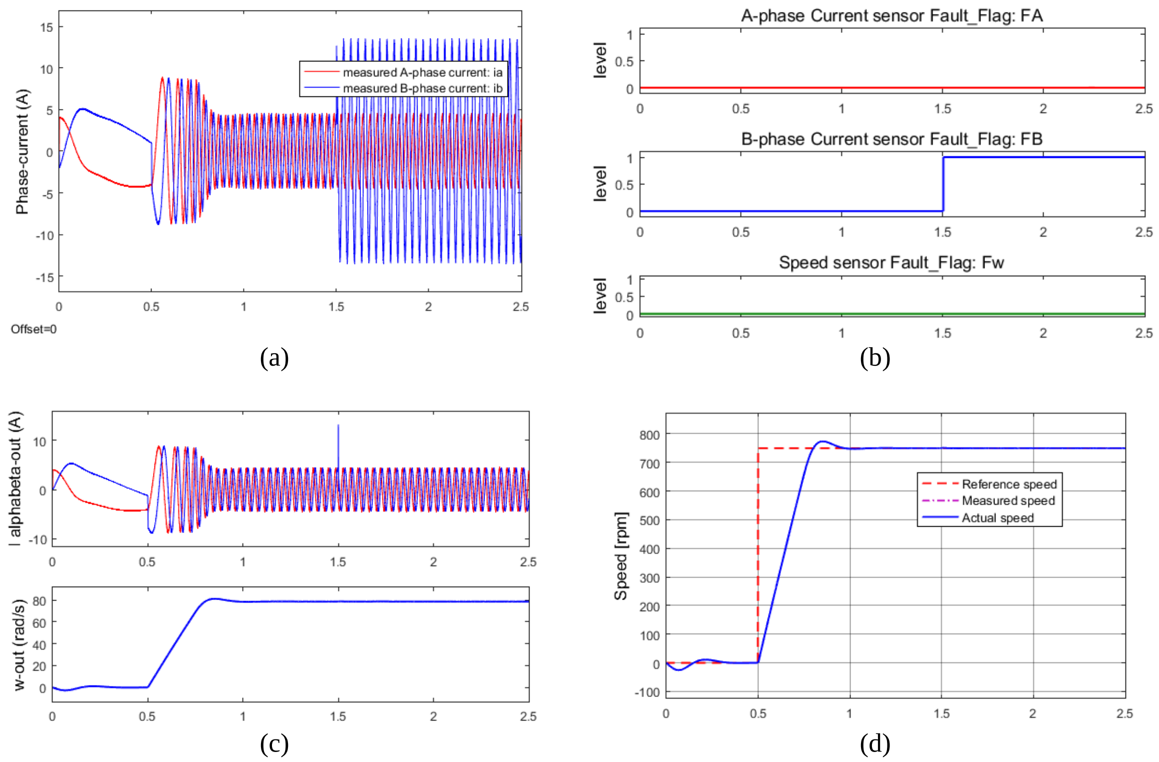

Figure 6. Scaling fault at B-phase sensor: (a) measured currents, (b) indicators, (c) outputs of FDI, and (d) motor speeds

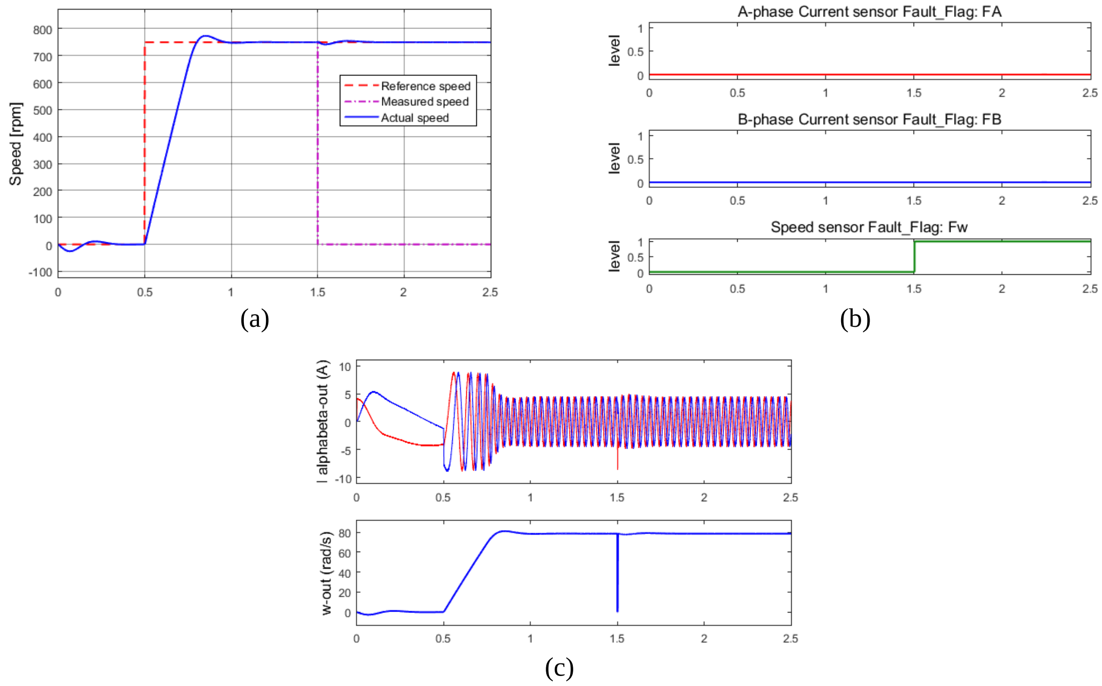

Figure 7. Open circuit fault at speed sensor: (a) motor speeds, (b) indicators, and (c) outputs of FDI

In the last case, random noises are simulated to check the accuracy of the sensor fault diagnosis (Figure 8(a)). The FT control function integrated into the FDI unit operated correctly without mismatch. The fault indicator remains low in this case (Figure 8(b)), and the signals provided for the control loop are still the sensor signals (Figure 8(c)), corresponding to Table 1. The IMD still works with the feedback sensor signal in the speed control, shown as the actual speed in Figure 8(a). The proposed FT control method has accurately diagnosed each sensor fault through the above three simulations and is not confused with random noise in the last simulation. The current and speed signals are according to the IMD system's operating state to ensure the stability and reliability of the control process.

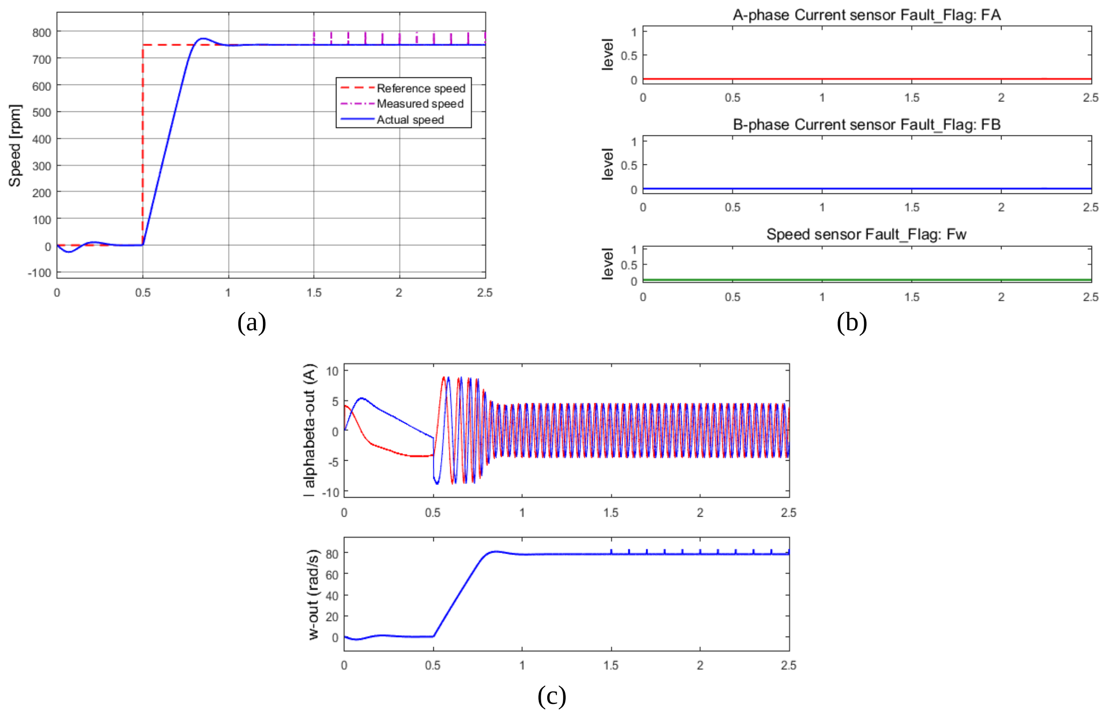

Figure 8. Random noise at speed sensor: (a) motor speeds, (b) indicators, and (c) outputs of FDI

4. CONCLUSION

An FT control technique against sensor failures, including the speed sensor and current sensor of an IMD system, is presented in the paper. The fault diagnosis technique consists of two core algorithms: TDO and a comparison algorithm of the measured and estimated signals. The TDO algorithm is used to recognize the initial fault sign, and the comparison algorithm is used to verify that the fault has occurred. After the operating status of each sensor has been determined, the FDI unit will provide the measured signals in the case of regular operation and the corresponding estimated signal in sensor fault cases. The method's efficiency has been demonstrated by accurately diagnosing each fault case and not being confused with random noises. After the fault state is determined through the fault indicator flags, the estimated signals are used to replace the incorrect measured signal to sustain the operation of the IMD system corresponding to the appropriate sensorless mode. In case random noise occurs, the FT control function is not activated, and the signals provided to the controller still have measured signals.

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BIOGRAPHIES OF AUTHORS

Minh Chau Huu Nguyen is a lecturer in the Faculty of Electrical-Electronics Engineering at Vietnam Aviation Academy. He graduated from the Military Technical Academy, in Vietnam, and received his ME degree in Automation Engineering in 2012. He is researching at the Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava, Czech Republic. His research interests include automatic control systems, intelligent control systems, electrical machines, apparatus, and drives. He can be contacted at email: minhnhc@vaa.edu.vn.

Cuong Dinh Tran is a lecturer in the Faculty of Electrical-Electronic Engineering at Ton Duc Thang University. He received his BE, and ME degrees from Ho Chi Minh City University of Technology, Vietnam, and his Ph.D. from the VSB-Technical University of Ostrava, the Czech Republic, in 2005, 2008, and 2020. His research interests include modern control methods and intelligent algorithms in motor drives. He can be contacted at email: trandinhcuong@tdtu.edu.vn.