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Design and Simulation of Current and Speed Sensors to Diagnose Induction Motor Drive Faults

Alli Ramya[1], Arpula Krishnaiah[2], Maisakhsi Pavan kumar[3]
[1]Electrical and Electronics Engineering & KLR Engineering College, Palvancha Telangana
[2]Electrical and Electronics Engineering & KLR Engineering College, Palvancha Telangana
[3]Electrical and Electronics Engineering & KLR Engineering College, Palvancha Telangana
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Abstract
The research suggests the use of the current space vector of measured stator currents to diagnose faults in speed and current sensors in field-oriented control of induction motor drives. The faults of the speed sensor are detected through the comparison algorithm between the reference rotor speed and the measured speed. A counter mechanism is added to the diagnostic process to reduce the impact of encoder noise on the diagnostic process. The present strategy contributes to the autonomy of the diagnostic phases of the fault-tolerant control (FTC) scheme by removing the use of estimated variables in speed sensor fault detection. Besides that, a new method, which involves an addition of the existing space vector with delayed function, is brought to realize the actual detection of current sensor faults as well as be able to differentiate between current sensor faults and speed sensor faults. The given approach is verified by the means of MATLAB/Simulink simulations, and the obtained results prove the efficiency of the diagnosis method of induction motor drive systems.
Keywords: ***Fault-tolerant control, diagnosis, induction motor, FOC, sensor less control.***

1.Introduction
Induction motor drive (IMD) systems have been the most popular type of drive used in an industrial application, electric vehicles, HVAC systems, and household appliances. Over the last several years, a great number of challenges relating to nonlinear control methods were solved, which made IMDs even more popular. Traditional IMD system comprises of four essential parts such as an induction motor, power converter, measurement sensors and a controller (1). The controller uses sensor feedback signals to compare against reference values to create the appropriate control commands to the power converter in order to control the motor speed and torque.

The quality of hardware and the effectiveness of the control algorithms especially the sensor subsystem is of critical importance to the overall performance of an IMD system. Consequently, sensor fault diagnosis has become a serious research issue in IMD control in recent years. To provide safety and reliability in industrial applications (conveyor belts, ventilation systems, and electric vehicles) fault-tolerant control (FTC) capabilities must be integrated into control systems (2), (3).

The strategies used by FTC are usually divided into two as passive FTC (PFTC) and active FTC (AFTC) (4). PFTC schemes are capable of only dealing with restricted cases of fault, and usually run offline. Conversely, the AFTC schemes are more functional since they have the ability to cure the complicated sensor failure in real-time. The AFTC system is characterized by three major steps, which are fault diagnosis, fault isolation and system reconfiguration (4).

Speed encoders, phase current sensors and DC-link voltage sensors are the most frequently used sensors in IMD systems. Speed and current sensors are becoming more essential than voltage sensors in modern control schemes where the voltage signals may be substituted by reference voltages in the control loop. This paper therefore aims at coming up with a better AFTC strategy to deal with speed and current sensor faults.

The majority of the current methods of diagnosing the fault of speed sensors are based on the observation of the difference between the rotor speed and an estimated one. This deviation is compared against a set limit in order to identify a fault. As an illustration, (5) demonstrated the application of an extended Kalman filter (EKF) to estimate the rotor speed and sensor fault detection through the comparison of the estimated and measured rotor speed. Generalized internal model control and hybrid FTC were also suggested as the strategies of reconfiguration, where the effectiveness of the strategies is evidenced by the results of the simulation.

The other method used in (6) used an adaptive stator flux observer to calculate rotor speed. The error between the estimated speed and the measured speed signal was used to detect fault and filtered by low-pass filter and compared against a threshold. Furthermore, a maximum-likelihood voting-based diagnosis approach was suggested to

identify the fault in speed sensors by integrating the feedback speed signals with the estimated speeds as determined by an EKF and a Luenberger observer. This technique had a high level of diagnostic accuracy over a broad range of speed of simulation and experimentation.

Another approach was suggested in (8) that used measurements of stator current to detect faults in speed sensors. The good separation in the diagnosis and reconfiguration stages is one of the benefits of this method. In this technique, sensorless control is implemented using model reference adaptive system (MRAS) during a reconfiguration and the fault detection is done using estimated currents.

The control technique of IMDs has been made more common today by field-oriented control (FOC) first proposed by Hasse (1969) and Blaschke (1972). Stator currents are a core part of FOC, allowing the control of torque and flux to be precise (9)(10). In FOC, stator current is decomposed to two orthogonal components, one running along the rotor flux and the other perpendicular to the rotor flux. The y-axis current is the controller of electromagnetic torque and the x-axis current is the one that regulates rotor flux.

2. Control Strategy

The sensorless control strategy is used to reconfigure the IMD controller structure in order to close the sensor failure event. The proposed FTC method is set to manage both speed sensor fault and a current sensor fault though it is supposed that there is only one type of sensor fault at a given time. In reality, the likelihood of the speed sensor and current sensor failure are very minimal.

In case the speed sensor malfunctions when having at least two current sensors working, the suggested approach provides the stable running. Equally, when the speed sensor is healthy, the system would also be able to run reliably even when two current sensors fail. The faulty sensor phase may also be determined using the proposed diagnostic strategy and the difference between the current sensor faults and speed sensor faults can also be clearly defined.

The suggested solution is worked out on the basis of practical considerations and the specifics of FOC-based IMDs. The key findings of this research are as follows:

Speed Sensor Fault Diagnosis

The other approach offered is a new way of identifying the faults of speed sensors through comparing the measured speed with the expected speed of the rotor. The fault is only confirmed with a time counter when the difference is observed to remain inconsistent over a set period hence effectively reducing the effect of noise. Execution time of speed sensor fault detecting process is 3 ms and can support zero-speed fault, low-speed fault, and high-speed fault.

Present Current Sensor Fault Diagnosis

A delay-based algorithm is presented in order to detect faults in phase current sensors. This technique, which compares the previous sampling cycle stored value of a sinuoidal current signal with the current instantaneous value, is used. The algorithm is computationally efficient, reliable and the algorithm is easy; hence, it is easy to use in real-time industries.

Robust FTC Performance

The suggested FTC strategy will allow stable operation either with a defective speed sensor and healthy current ones or defective current sensors and healthy speed sensor. The proposed method effectively handles low-speed operation issues as compared to the traditional sensorless control methods, which are normally slow in operation owing to the sensitivity of the parameters as well as the nonlinearities of the inverters [17].

The efficacy of the given solution is proved by the simulation of the approach in MATLAB/ Simulink and experimental work. Findings prove to be able to perform reliably in different fault modes especially at low operating speed ranges. The paper is structured in the following way: Section 1 is the introduction to the research topic, Section 2 describes the mathematical modeling of the IMD and the suggested algorithm, Section 3 and 4 provide the discussion of simulation and experimental results, respectively, and Section 5 summarizes the paper and draws future research directions.

3. Simulation Analysis

A number of simulation studies are carried out to test the proposed FTC strategy in the IMD measurement system when various faulty circumstances occur. The sensorless control techniques usually have problems with low-speed operation (around 10% of rated speed) because of the nonlinearities of the inverter and nonlinearity of the

parameters. Accordingly, there will be no simulations done in the higher speed section, and the motor will be operating at 10 percent of the rated speed.

The IMD measurement system has two current sensors and a single speed sensor as indicated in Fig. 1. Table 3 gives the motor parameters in use in the simulations. The operating condition as shown in Fig. 5 is related to a speed ramp of zero to 10 per cent of the rated speed (150 rpm) in the range 0-0.1 s, thenceforth, the speed remains constant.

3.1 Speed Sensor Fault Scenario

The induction motor is used in the first simulation in a normal condition until the speed sensor fails suddenly at 2.0 s. Consequently, the feedback speed signal reduces to zero. The fault is identified after 30 cycles of sampling using the proposed diagnosis algorithm, which assesses the discrepancy between the reference speed of rotor and the measured signal of rotor speed. The missing speed feedback will be substituted by the approximate rotor speed to enable the IMD to keep on running smoothly as indicated in Fig. 6.

A scenario involving partial current sensor fault is the third scenario that will be discussed.

In the second simulation, there is a scaling fault in the phase-A current sensor at 2.0 s. The faulty sensor signal is very different as shown in Fig. 7(a) as compared to healthy sensor signals. The suggested current sensor diagnosis algorithm identifies the fault in 35 sampling points. Afterwards, FTC system feeds the measured currents with an estimate to the FOC controllers. A momentary speed and fluctuation takes place but the motor stabilizes very quickly as shown in Fig. 7(c). The diagnostic flags in Fig. 7(d) have confirmed that only there is a current sensor fault detected and not a false detection of a speed sensor fault.

3.3 Full Current Sensor Failure Condition

The last simulation takes into account the total failure of the phase-C current sensor at 2.0 s. As indicated in Fig. 8(a) the current signal measured is lost and the delayed-current comparison gives zero. This fault was noted by FTC system and the faulty phase-C signal and the healthy phase-A signal are replaced by estimated currents in 20 sampling cycles. The FTC response is made easier and quicker in this strategy.

The motor speed process is constant during the fault condition as illustrated in Fig. 8(c) with little oscillations because the fault compensation is done with great speed and precision. By comparing Figure 8(d) with the location and type of fault, it is clear that the diagnosis algorithm is able to detect the fault properly by turning on the corresponding diagnostic flags.

4.Simulation Results

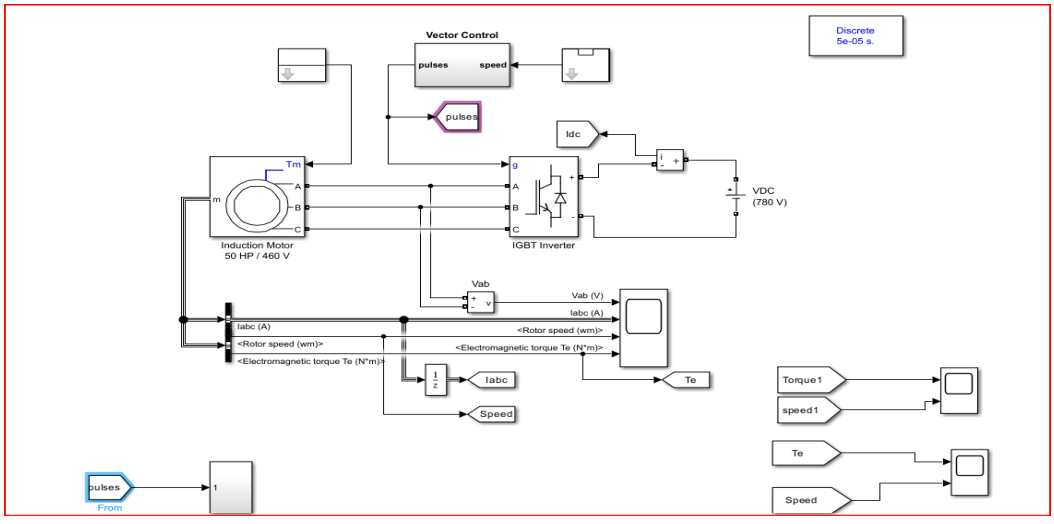

FIGURE 1 Simulation overall system diagram

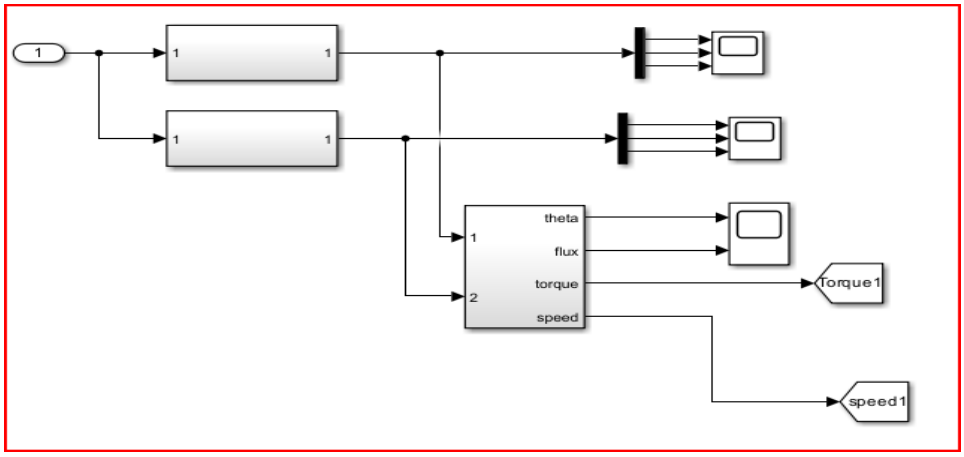

FIGURE 2 Switching Analysis

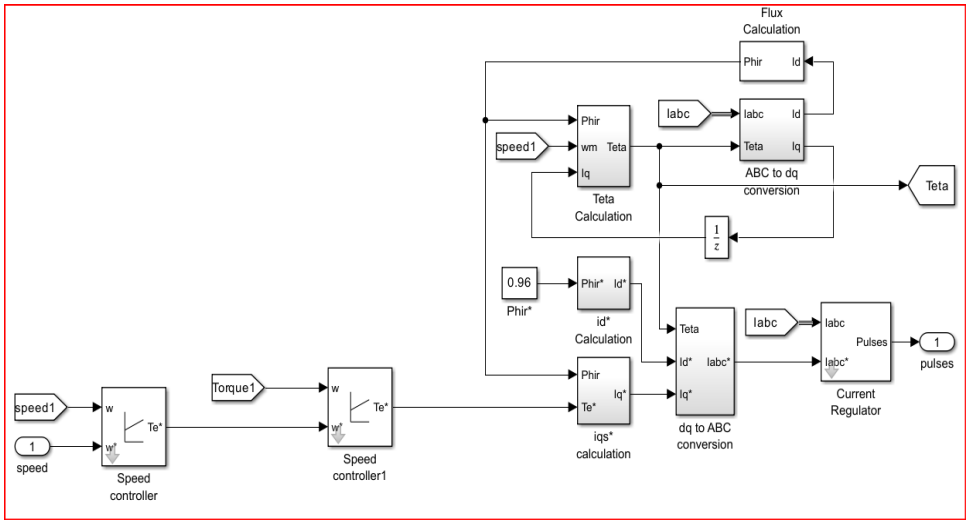

FIGURE 3 Control Strategy

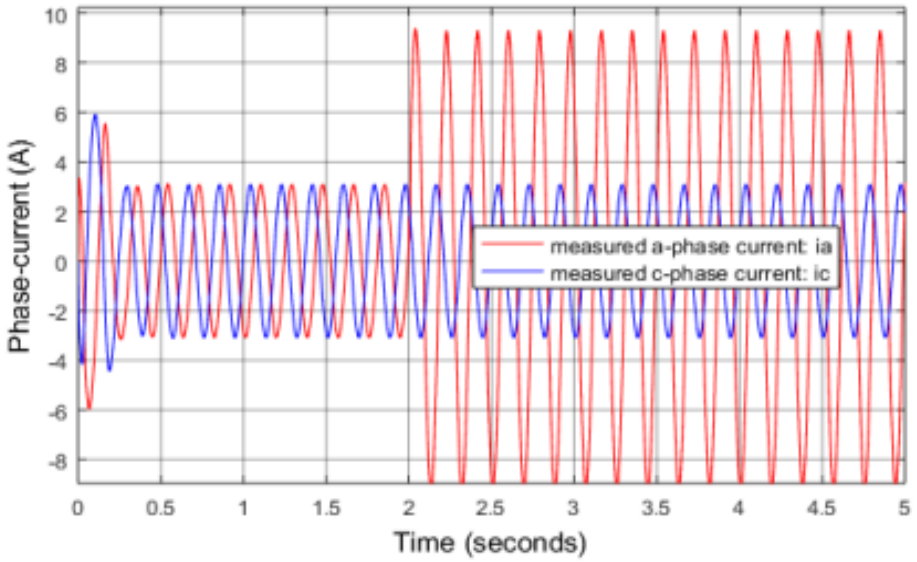

FIGURE 4 Measured current

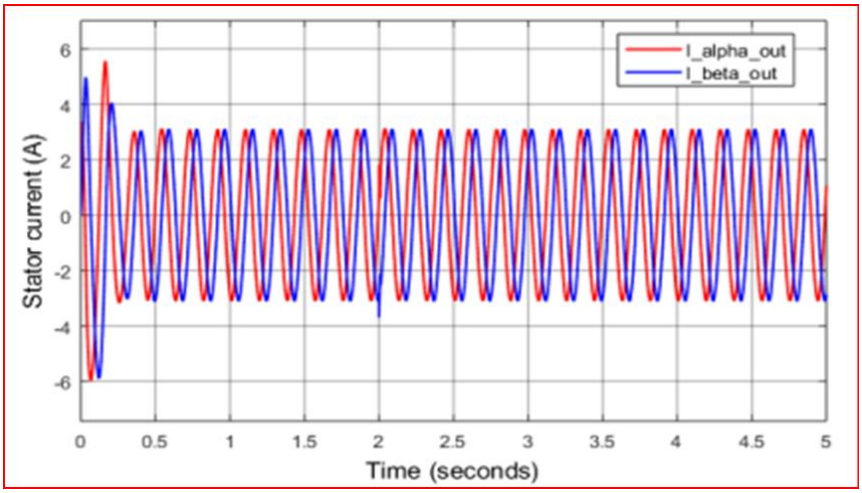

FIGURE 5 Components of FOC Current

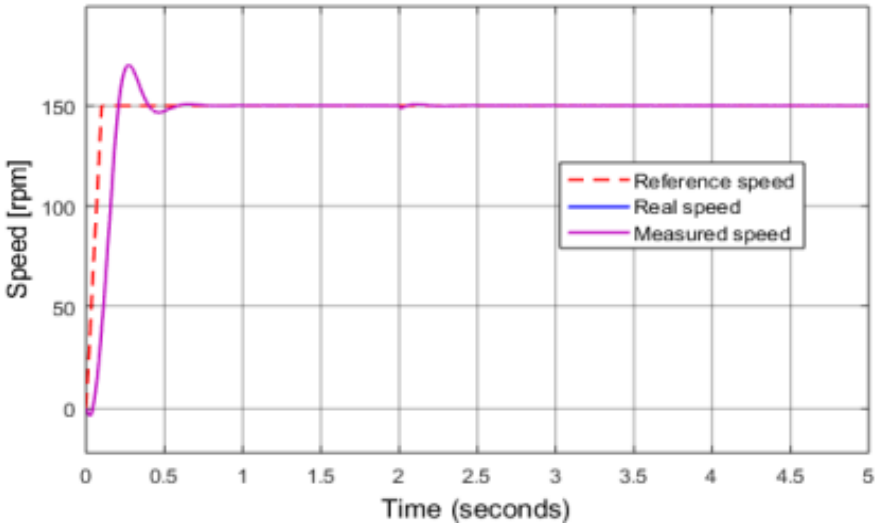

FIGURE 6 Reference, real and measured rotor speed

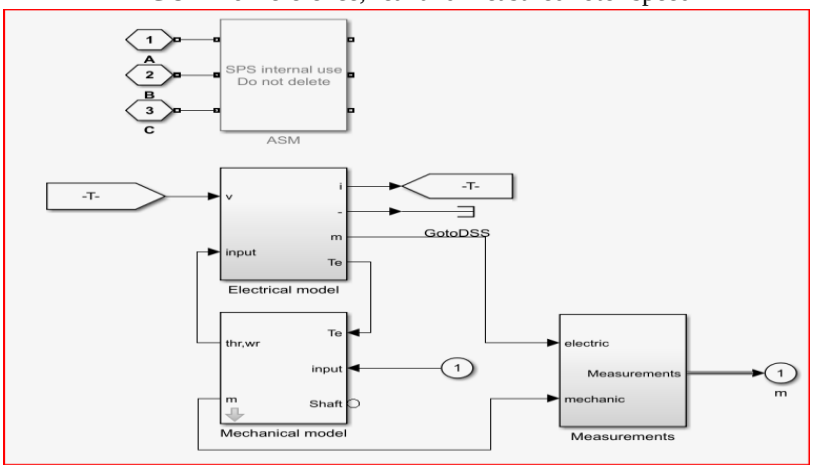

FIGURE 7 Programming Language in Code Composer Studio(CCS) Programming

Three sensor faults that were experimentally investigated to study the consistency between simulation and experimental results included: a speed sensor fault, a current sensor scaling fault and a complete sensor fault. The entire experiment was performed in low-speed operating range with the motor speed adjusted at 150 rpm, which is 1/10 th of the rated speed. The working condition of the IMD was characterized by ramping speed between zero and 150 rpm at the period between 0 and 0.1 s, and steady-state between 0.1 and 1.5 s.

The induction motor in the first experiment works normally between 0 to 2.0 s and this was demonstrated in Fig. 10(a). At 2.0 s, the speed sensor malfunctions abruptly and the feedback signal goes to zero and the measured

speed information is lost. The proposed speed sensor diagnosis algorithm will quickly alarm the fault by presenting the sensor feedback signal against the reference rotor speed after 30 sampling cycles. The diagnosis algorithm requires a running time of about 3 ms, in the light of the fact that the processing cycle of the DSP is approximately 100 μs. When the lost feedback signal has been substituted by the estimated rotor speed, the IMD enters fault-tolerant control mode. The actual motor speed, as shown in Fig. 10(a), still remains steady and keeps following the reference without any sharp changes but the performance is marginally worse than with normal operation with a healthy speed sensor.

5. Conclusion

The purpose of this paper is to suggest a new method of fault diagnosis of the system controlling the speed and current sensors fault-tolerant of induction motors drive system. The suggested approach proves to be very effective when dealing with various sensor faults. The fault diagnostic algorithm of the speed sensor is able to identify errors of measurement of the speed reliably and it is resistant to noise of random pulses. The proposed delay-based algorithm is useful in identifying severe current sensor faults, including total loss of signal, within a short period of time, whereas other types of current sensor faults are also accurately detected but not confused with speed sensor faults. The proposed diagnosis strategy is easier to structure in comparison with the current detection methods, which leads to a decrease in computational complexity, accelerated execution, and the cost of hardware when operating under the same conditions. The effectiveness and reliability of the proposed approach are both proven by both simulation and experimental results. The further development will be aimed at improving sensor fault diagnosis performance in the case of transient operating conditions.

Acknowledgement: Nil

Conflicts of interest

The authors have no conflicts of interest to declare

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