1. Introduction

The DSIM is a multiphase machine that is widely used due to its advantages such as power segmentation, the ability to operate in the event of failure of one of the stars, and reduction in stress on the converters [1–3]. The control of the DSIM is generally provided by PI controllers, but because of the sensitivity of these controllers to the variation of machine parameters, nonlinear controllers are often used which are insensitive to disturbances, whether parameter variations or load variations. In this paper, the control problem of this machine is solved using the Active Disturbance Rejection Control technique.

This type of controller has proved its efficiency in several publications [4]. It allows us to estimate and compensate in real time all the disturbances, both internal and external (variation of the machine parameters and variation of the load) [4, 5].

The performance of this control approach depends on the operating status of all elements of the system. Faults can affect any part of the system (Figure 1), and those related to sensors are the most common. In the present paper, the faults affecting current sensors are addressed. These faults can cause serious system malfunctions and degradation of its performance [6].

The fault-tolerant control is a strategy that allows us to ensure the efficiency and continuity of the machine operation. In literature research, several methods of FTC are applied for the detection and reconfiguration of current sensor faults. In [7], a redundancy method is applied; in general, this method is not experimental on the cost side. In [8], a logical decision method is used to detect a single fault. Another method proposed in [9] allows us to use a detector based on neural networks. A neural network algorithm is implemented to detect the fault, and then a logic circuit is used as a compensation unit. The work developed in [10] proposes a new FTC approach for the DSIM system. This presented method compares the estimated current values with the measured ones; a state observer is used to calculate the currents from the voltages (voltage sensors).
Other methods using two current sensors are as follows. Chakraborty and Verma [11] developed a new method of FTC by using axes transformation. In [12], a method was studied based on the use of a TDO to detect the existence of the fault. A voltage synthesizer is used to calculate the voltages of each phase from DC voltage and switch signals. Rothenhagen and Fuchs [13] developed a method based on the bilinear observer. In [14], a fault detector based on a neural network is proposed. In comparison with the methods of the FTC proposed in [7–14], the methods studied in [7–10] allow us to detect only one default in addition that they are not economical because three sensors are used. The methods proposed in [11–14] are practically economical (two sensors are used), and they allow us to detect one or both sensors’ default.

There are two types of fault-tolerant commands, namely, passive and active [15]. The passive fault tolerant command is based on the robustness of the controllers such as backstepping regulator. This regulator is designed to take into account the errors of modelisation and the uncertainty of measurement. The active command consists in implementing an algorithm to detect, isolate, and compensate the sensor default [15–17].

In this work, the active control (AC) is adopted because of its advantages over the passive control, in particular its ability to compensate for the different types of faults that can affect the sensors.

The proposed tolerant control technique is based on the estimation of stator currents and its comparison with the measured currents. The residue of this comparison is introduced into a logic circuit allowing the detection and isolation of the fault and then the reconfiguration of the control.

Three types of sensors are used in our machine converter system: a speed sensor, a current sensor, and a DC voltage sensor. The purpose of the DC bus sensor is to protect and ensure the continuity of service of our system in the event that the current sensors are defective. The measurement of the DC bus and the switching states of the converters are sufficient to reconstruct the phase currents of the machine.

Motivated by the abovementioned observations, the present paper proposes a robust tolerant control for current sensor measurement faults of the DSIM system. The proposed method has the advantage of avoiding the error of estimation of the observers’ gains that are often used. The method is based on the use of a stator current estimator based on the mathematical equations of the machine and the use of two voltage observers.

The rest of this paper is organized as follows: Section 2 gives the modeling of the double star induction machine in Park’s frame and presents its vector control based on ADRC regulators. In Section 3, the estimators allowing the reconstruction of the stator currents and the algorithm for the fault-tolerant control of the current sensors are presented. In Section 4, the simulation results of this tolerant control strategy are given, and Section 5 concludes this paper.

2. System Model

This section tackles to the problem of the system modeling. Figure 2 illustrates the synoptic diagram of our system. The symbol \( \ast \) signifies the reference value of the magnitude.

This system is composed of a set of the following elements:

DSIM: this machine is the essential element of our system; it is used in motor operation and is composed of two stators and a cage rotor [18].

Estimator: it is used to estimate the rotor flux \( \psi_r \), and the stator pulsation \( \omega_r \). From the systems of equations of voltages and fluxes in DSIM [18] and by using the principles of rotors field-oriented control (\( \psi_{dr} = \psi_r \) and \( \psi_{dr} = 0 \)), we deduce equations (1) and (2) of the rotor flux and the stator speed, respectively:

\[
\psi_r = \frac{L_m}{1 + Tr} (ids + id_2),
\]

\[
\omega_r = \frac{R_r L_m}{L_r + L_m} \left( i_{qs} + i_{q2} \right) / \psi_r
\]

Converters: the double star induction machine is generally powered by two voltage inverters controlled by the PWM technique. Each converter provides power to one of the stars of the DSIM [19].

PI controller: it is important to note that the speed and flux are regulated by an IP type and a PI controller, respectively, since they allow us to cancel the overtaking of the speed.

ADRC controller: this command consists in implementing ADRC regulators in the stator current regulation chain of the DSIM. Figure 3 shows the block diagram of the first-order ADRC regulator that we used in this study.

The references [20–22] explain the different magnitudes of the first-order ADRC.

Sensor: it is used to measure the electrical or mechanical magnitudes of the machine [23]. Three types of sensors are used in this system: two stator current sensors from each star, a speed sensor, and a DC bus sensor. The failure of one of the sensors leads to serious operating problems. There are three types of current sensor faults:

Gain defect: the signal transmitted by the sensor is an amplified or attenuated signal.
Offset defect: the received signal is not a zero-centered signal.
3. Fault-Tolerant Control

The fault-tolerant control plays an interesting role after a current sensor fault has occurred. This command is able to detect the existence of a fault, isolate it, and compensate it instantly.

3.1. FTC Applied to the DSIM. Figure 4 represents the system studied by taking into account faults in current sensors and integrating fault-tolerant control.

The control is based on the use of two current sensors for each stator and two stator current estimators. We work in the Clark frame \( \alpha \beta \) illustrated in Figure 5. Figure 5 illustrates the axes of each stator, where \( a_1, b_1, \) and \( c_1 \) are the axes of the first stator and \( a_2, b_2, \) and \( c_2 \) are the axes of the second stator. \( \alpha \) and \( \beta \) are the axes of Clark’s coordinate system, where \( \alpha \) is confused with \( a_1. \)

The transformation matrix of the components of star 1 towards the referential \( \alpha \beta \) is given by:

\[
\begin{bmatrix}
i_{a1} \\
i_{b1}
\end{bmatrix} = \begin{bmatrix}
\frac{3}{2} & 0 \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
i_{a1} \\
i_{b1}
\end{bmatrix}.
\]

The transformation of the components of star 2 to \( \alpha \beta \) is given by:

\[
\begin{bmatrix}
i_{a2} \\
i_{b2}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
\frac{3}{2} & \frac{3}{2}
\end{bmatrix} \begin{bmatrix}
i_{a2} \\
i_{b2}
\end{bmatrix}.
\]

The system of equation (5) represents the transformation of the reference frame \( d, q \) to \( \alpha, \beta: \)

\[
\begin{bmatrix}
i_{a1,2} \\
i_{b1,2}
\end{bmatrix} = \begin{bmatrix}
\cos(\theta_s) & -\sin(\theta_s) \\
\sin(\theta_s) & \cos(\theta_s)
\end{bmatrix} \begin{bmatrix}
i_{d1,2} \\
i_{q1,2}
\end{bmatrix}.
\]

Figure 6 illustrates the flowchart allowing us to decide which value of the measured or estimated currents will be chosen. After the calculations of \( i_{a1}, i_{b1} \) from the measured values \( i_{a1}, i_{b1} \) and the calculations of \( i_{a1ES}, i_{b1ES} \) from the estimated values, we compare the measured currents to their estimated equivalents. If the difference between these currents is greater than a well-defined threshold, it is the estimated currents that will be considered and used in the control chain.

The algorithm of this command is presented in Figure 7. This algorithm calculates the difference between the measured currents and those estimated and then compares the
The absolute value of the resulting error of this operation to a threshold. The purpose of this comparison is to detect if one or both sensors are defective. A switch block is used to select the phase current.

The threshold must be well selected to ensure the best performance. There are no rules to determine this threshold; it can be selected based on experience.

3.2. Current Estimation. The estimation of stator current is based on the calculation of the stator voltages; by using the DSIM equations, the stator currents will be calculated. Voltage observers are designed to calculate the stator voltage from the switching states of the converters, and the DC voltage is measured by using the DC bus sensor [24].

The system of equation (6) represents the stator voltages of star 1 as a function of the continuous voltage $E$ and the switching states $f_{a,b,c1}$ [25]:

$$
\begin{align*}
V_{a1} &= \frac{E}{3} (2f_{a1} - f_{b1} - f_{c1}), \\
V_{b1} &= \frac{E}{3} (-f_{a1} + 2f_{b1} - f_{c1}), \\
V_{c1} &= \frac{E}{3} (-f_{a1} - f_{b1} + 2f_{c1}).
\end{align*}
$$
Once the stator voltages are calculated, we determine the stator voltages $V_{ds1}$ and $V_{qs1}$ in the park reference ($d, q$). The stator voltages of star 2 are determined in the same way as star 1.

We calculate now the stator currents by using the equations of the DSIM [26] and by applying the principle of field-oriented control $\dot{\psi}_s = \psi_r$ and $\psi_{qr} = 0$. The stator currents are therefore expressed by the following relationships:

$$i_{ds1} = \frac{1}{L_s} + e \left[ \int V_{ds1} - R_s i_{ds1} - e i_{ds2} - d \psi_r + \omega_s (L_s + e) i_{qs1} + e i_{qs2} \right]$$  \hspace{1cm} (7)

$$i_{ds2} = \frac{1}{L_s} + e \left[ \int V_{ds2} - R_s i_{ds2} - e i_{ds1} - d \psi_r + \omega_s (L_s + e) i_{qs2} + e i_{qs1} \right]$$  \hspace{1cm} (8)

$$i_{qs1} = \frac{1}{L_s} + e \left[ \int V_{qs1} - R_s i_{qs1} - e i_{qs2} - \omega_s ((L_s + e) i_{ds1} + e i_{ds2} + d \psi_r) \right]$$  \hspace{1cm} (9)

$$i_{qs2} = \frac{1}{L_s} + e \left[ \int V_{qs2} - R_s i_{qs2} - e i_{qs1} - \omega_s ((L_s + e) i_{ds2} + e i_{ds1} + d \psi_r) \right]$$  \hspace{1cm} (10)

where $e$ and $d$ are constants:

$$e = \frac{L_m L_r}{L_s + L_m}$$  \hspace{1cm} (11)

$$d = \frac{L_m}{L_s + L_m}$$

Figure 7: Defect algorithm.

4. Simulation

The proposed fault-tolerant control algorithm is implemented in the MATLAB/Simulink environment to test its robustness and performance in the presence of sensor defects. Two types of defects are considered in this article:

- The gain defect for which we multiply the amplitude of the measured signal (phase current) by a gain of 0.3
- The offset fault where we add a constant equal to 5 A to the measured value

In this case, we introduce two types of defects: a) the gain of the current sensors is 0.3 and b) an offset of 5 A is added into the current sensors. The stator currents are calculated by equations (7) and (8).

It should be noted that this method is only applied for current sensor faults and not for the actuator faults.

Two current sensors are used in the proposed control for each stator: one is placed on phase $a$ and the other on phase $b$. Two tests are performed in this section. The first test consists in testing the implemented command in the presence of a defect on phase $a$ of each star. In the second test, we assume that all current sensors are faulty.

The machine is controlled by ADRC regulators which have shown their performance and robustness in controlling the electrical and mechanical magnitudes of the machine.

The DSIM operates with a speed of 100 rad/s. It operates at no load until time $t = 1$ s when we introduce a load torque of 12 N-m.

4.1. The Sensor of a Phase Is Faulty. Figures 9 and 10 illustrate the operation of the DSIM when empty and under load. It is clearly observed that each variable (speed, torque, and flux) follows its setpoint. At the instant $t = 2.54$ s, we introduce a gain defect illustrated at the level of phase $a$ of each star. Figure 9 illustrates the evolution of the electrical and mechanical magnitudes of the DSIM in the presence of this defect. After the detection of this fault, the speed remains stable and insensitive to the presence of the fault. The stator current estimator allows the value and shape of the current to be preserved after the appearance of the fault. The reconfiguration of the control system following the sensor fault has allowed the torque and electromagnetic flux not to
deviate from their setpoints. Figure 10 illustrates an offset fault introduced at time $t = 2.565$ s. We note that the measured current $i_{s1}$ is shifted upwards at $t = 2.565$ s. Thanks to the FTC command, the erroneous measurement of the current sensor did not disturb the operation of the machine. All magnitudes have retained their dynamics.

4.2. The Two Sensors Are Faulty. Under the same operating conditions as before, this time, two current sensors are in default. Figure 11 shows the operation of the DSIM in the presence of gain faults, and Figure 12 illustrates its operation in the presence of offset faults. The stator currents are perfectly estimated from measurements of DC bus voltages and the switch functions of electrical power converters. Thanks to the algorithms implemented in the FTC control, all electrical and mechanical quantities maintain their stability and the performance of the DSIM is maintained as it was before the occurrence of current sensor faults.

In comparison with the methods of the FTC proposed and the method cited in [11], both methods use two sensors, a logic algorithm, and an estimator of stator currents and allow us to detect one or more faults. The logic algorithm proposed in our method is simpler than the other in [11]. The estimator of the stator current of [11] is from the current reference; this estimator is not valid when
Figure 10: Offset defect in a.

Figure 11: Continued.
the sensor defects at the beginning of machine operation because when the sensor is defected, at the beginning, the current reference is not correct so the estimator becomes invalid, but the estimator in our method is valid every moment because our estimator is independent of the measured current.

5. Conclusion

This article examined the fault-tolerant control of a double star induction machine in the event of a current sensor fault. The proposed technique does not require the use of any other sensor; it allows us to reconfigure the faults of the
current sensors. It works well in case of one or more faults, which increase the robustness of the DSIM and the reliability of the system.

This technique is essentially based on a stator current estimator, a fault detection and isolation algorithm, and robust ADRC controllers. The implemented algorithm is based on the estimation of stator currents from the measurement of the DC voltage of the power converter and the comparison of these estimated currents with those measured. This comparison makes it possible to detect the existence of a fault and isolate the faulty sensor.

The proposed method has proven its efficiency and robustness against different current sensor faults.

Abbreviations

\[ V_{ax1}, V_{bx1}, \text{and} \ V_{cx1} \]  
\[ V_{dx1}, V_{dx2}, V_{qx1}, \text{and} \ V_{qx2} \]  
\[ f_{a,b,c1,2} \]  
\[ i_{a1}, i_{b1}, \text{and} \ i_{c1} \]  
\[ i_{a2}, i_{b2}, \text{and} \ i_{c2} \]  
\[ i_{d1}, i_{d2}, \text{and} \ i_{q1} \]  
\[ i_{q2} \]  
\[ i_{d1ES}, i_{d2ES}, i_{q1ES}, \text{and} \ i_{q2ES} \]  
\[ i_{a1ES}, i_{a2ES}, i_{b1ES}, \text{and} \ i_{b2ES} \]  
\[ \psi_{dr}, \psi_{d1}, \psi_{d2}, \text{and} \ \psi_{q1} \]  
\[ \psi_{d}, \psi_{q}, \psi_{d1}, \psi_{d2}, \text{and} \ \psi_{q2} \]  
\[ \psi_{dr}, \psi_{d1}, \psi_{d2}, \text{and} \ \psi_{q} \]  
\[ C_{r} \]  
\[ R_{S1} \text{ and} \ R_{S2} \]  
\[ R_{r} \]  
\[ L_{S1} \text{ and} \ L_{S2} \]  
\[ L_{r} \]  
\[ L_{m} \]  
\[ \omega_1 \]  
\[ \alpha \]  
\[ \beta \]  
\[ \omega \]  
\[ \omega_{1} \]  
\[ \omega_{2} \]  
\[ \psi_{r} \]  
\[ \psi_{s} \]  
\[ \psi_{d} \]  
\[ \psi_{q} \]  

Voxes of star 1

Voltages of stators 1 and 2 in the \( d-q \) axis, respectively

Switching states of stars 1 and 2, respectively

Currents of star 1

Currents of star 2

Measured value of currents of star 1 and 2 in the \( d-q \) axis, respectively

Measured value of currents of star 1 and 2 in the \( \alpha-\beta \) axis, respectively

Estimated value of currents of stators 1 and 2 in the \( d-q \) axis, respectively

Estimated value of currents of stators 1 and 2 in the \( \alpha-\beta \) axis, respectively

Selected value of currents of stators 1 and 2 in the \( d-q \) axis, respectively

Flux of the rotor

Rotor flux component in the \( d-q \) axis

Load torque

Stator resistances (stators 1 and 2)

Rotor resistance

Stator self-inductances (stators 1 and 2)

Rotor self-inductance

Cyclic mutual inductance between stator 1, stator 2, and rotor

Stator speed in rad/s

Angular speed

Rotor speed in rad/s.

Appendix

Parameters of the DSIM are as follows:

Rated power: 4.5 kW

Number of pole pairs: \( P = 2 \)

Stator and rotor resistors: \( R_{S1} = R_{S2} = 0.86 \Omega \) and \( R_{r} = 0.36 \Omega \)

Stator and rotor inductances:

\( L_{S1} = L_{S2} = 0.184 \text{ H and} \ L_{r} = 0.0246 \text{ H} \)

Mutual inductance: \( L_{m} = 0.0537 \text{ H} \)

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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