Operating of DSIM without Current and Speed Sensors Controlled by ADRC Control

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Abstract

This paper presents an operation of the double star induction machine (DSIM) without current and speed sensors controlled by active disturbance rejection control (ADRC). The operation of the machine, without current and speed sensors, is an economic and simple method. The main advantages of this method are the reconstruction of stator current phases and rotor speed using only one DC voltage. The method is very simple and effective. It is based on the information provided by a DC voltage and the switching states of the converters to reconstruct the stator voltages. After we use two voltages observers to estimate the current stator and the rotor speed. The performance and the effectiveness of this method are verified under different conditions of simulations in MATLAB/Simulink. The results of the simulation prove the ability of this method to produce the same performances of DSIM with the current and speed sensors.

1. Introduction

In high-power applications, the number of phases reduces the efficiency of the machine-inverter system. Therefore, increasing the number of phase is a solution to eliminate the disturbances caused by the inverter switches. Hence, the birth of multiphase machines [1–5].

In our study, we are interested in a multiphase machine called double star induction machine (DSIM). This machine presents a center of interest for the researchers since they have many advantages compared to other machines that are essentially due to its construction [6, 7].

To control the DSIM, it is interesting to measure the stator current and the speed using sensors [8, 9]. The failure of these types of sensors is very common. This is essentially due to noise, bad connection, high demand for currents, the environment that surrounds it, etc. The information supplied by the faulty sensor influences the control and leads to a degradation of control performance [10].

To minimize the problems related to sensor faults. The research is directed towards fault-tolerant control (FTC), this method shows its performance well in many jobs [11, 12]. Despite its performance on the technical side, this method has cost disadvantages, as it requires the use of an FTC system.

Another method focuses in eliminating the current and speed sensors. This method uses observers or estimators to reconstruct the stator current and the rotor speed [13–20].

In recent decades, research has focused on speed sensorless. Few of them studies the stator current sensorless. In this context, many approaches are used to estimate the stator current and the rotor speed.

In references [13–16], an economical and simple approach proposed to estimate the stator current from the information provided by two DC-link current sensors. This approach is simulated with the DTC control. Other method proposes the use of Luenberger observer, sliding mode observer, etc., to estimate the current and the rotor speed. These observers guarantee a very good performance [21].

Reference [22] proposes a current estimator from the reference rotor flux, rotor flux angle, and state variables.

Another method uses the reference values of stator current to estimate the stator current [23]. Other researches
use predictive methods to estimate speed and stator current [24–27], this predictive methods have shown their robustness against disturbances and the variation of machine parameters.

In the aim to avoid sensor faults and to find an economical and efficient solution, we focus our study on the operating of DSIM without AC current sensor and speed sensor.

The main motivation behind this work is to reduce the cost of the installation, simplify the wiring and the operation of maintenance, and increasing reliability.

The DSIM is controlled by rotor flux vector control based on ADRC regulators [28, 29]. This type of regulator has shown its efficiency to control the DSIM [29]. Only one type of sensor is used in our system machine-converter: a DC voltage sensor. The DC sensor is used to estimate stator current and rotor speed in absence of sensors. The DC bus measurement and the switching states are sufficient to reconstruct the phase current of the machine, and then to calculate the speed.

This paper is organized into three main parts. The first part describes the system component. The second part presents a machine model without current and speed sensors, two estimators of current and speed are presented. In the third part, we implement the model of the machine controlled by ADRC controllers with the estimators to MATLAB/Simulink, and we presented the results of a simulation. We finished the study with a conclusion.

2. Machine Model

Figure 1 presents the system studied in this paper. It is composed of a set of elements.

(i) Converter: the DSIM is powered by two three-phase inverters, controlled by the PWM control [6, 30].

(ii) DSIM: the double star induction machine is composed of two parts, one is the stator and the other is the rotor. The stator of the DSIM is composed of two windings coupled in a star, each winding consists of three phases offset from each other by an angle of $2\pi/3$ [31, 32].

The voltages and the flux equations of the DSIM are expressed as follow:

\[
\begin{align*}
V_{ds1} &= R_s i_{ds1} + \frac{d\Phi_{ds1}}{dt} - \omega_s \Phi_{qs1}, \\
V_{ds2} &= R_s i_{ds2} + \frac{d\Phi_{ds2}}{dt} - \omega_s \Phi_{qs2}, \\
V_{qs1} &= R_s i_{qs1} + \frac{d\Phi_{qs1}}{dt} + \omega_s \Phi_{ds1}, \\
V_{qs2} &= R_s i_{qs2} + \frac{d\Phi_{qs2}}{dt} + \omega_s \Phi_{ds2}, \\
0 &= R_s i_{ds} + \frac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs}, \\
0 &= R_s i_{qs} + \frac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds}.
\end{align*}
\]

(iii) DSIM control: the control of DSIM is ensured by vector control combined with active disturbance rejection control (ADRC). The purpose of the vector control is to achieve the decoupling between the magnitudes of this machine. The ADRC in turn makes the control robust against disturbances whether internal (variation of machine parameters) or external (variation of load). The integral-proportional (IP) regulator allows eliminating the speed overtaking.

The ADRC is a robust nonlinear command proposed by Han. The ADRC’s role is to estimate the disturbances reaching the system by an extended state observer. The structure of this control is presented in paper [29].

3. Machine Model without Current and Speed Sensors

The model of the double star induction machine without stator current and speed sensors is shown in Figure 2.

The proposed model uses a technique of estimation and reconstitution of stator current and rotor speed from a single DC voltage sensor.

The objective of the operation of DSIM without sensors is to overcome the failure arising on the system due to the failure of the current or speed sensors. The method contributes to the minimization of costs, simplification of the maintenance operation, and increasing reliability.

Blocks of estimators are added to replace the current and speed sensors, the estimators are based on the information provided by the DC bus sensor and by the switching states of the converters.

3.1. Stator Current Estimation. The estimator used in this paper is cited in reference [33]. It is based on the DSIM equations and the application of the principle of vector control $\Psi_{dr} = \Psi_s; \Psi_{qr} = 0$.

Figure 3 illustrates the steps in estimating stator current. The stator voltages are calculated from the measurements of the DC bus and the switching states of two converters. The following equations represent the relations connecting the stator voltages with voltage $E$ and switching states $f_{abc1,2}$.
Figure 1: Model of the system.

Figure 2: System without sensors.
From the stator current, we calculate the expressions of the rotor fluxes in the Clark reference illustrated by the following equations:

\[
\frac{di_{d2}}{dt} = \frac{1}{L_s + \epsilon} \left[ V_{d2} - R_s i_{d2} - e \frac{di_{q1}}{dt} - a \frac{d\Phi_r}{dt} + \omega_s \left( (L_s + e) i_{q1} + ei_{d2} + d\Phi_r \right) \right],
\]

\[
\frac{di_{q2}}{dt} = \frac{1}{L_s + \epsilon} \left[ V_{q2} - R_s i_{q2} - e \frac{di_{q1}}{dt} - d \frac{d\Phi_r}{dt} + \omega_s \left( (L_s + e) i_{d2} + ei_{q1} + d\Phi_r \right) \right].
\]

(8)

3.2 Speed Estimation. The rotor speed is estimated by a mechanical model. It is estimated from the stator current presented in Clark reference and the mechanical speed equation. From the stator current, we calculate the expressions of the rotor fluxes in the Clark reference illustrated by the following equations:

\[
\frac{d\Phi_{r\alpha}}{dt} = R_s d i_{a1} + R_r d i_{a2} - \frac{R_r}{L_r + L_m} \Phi_{r\alpha} - \omega_s \Phi_{r\beta},
\]

\[
\frac{d\Phi_{r\beta}}{dt} = R_s d i_{\beta1} + R_r d i_{\beta2} - \frac{R_r}{L_r + L_m} \Phi_{r\beta} + \omega_s \Phi_{r\alpha}.
\]

(9)

(10)

Using the values of the rotor fluxes and the stator current in the Clark reference, we calculate the torque by the following expression:

\[
C_{cm} = P \frac{L_m}{L_r + L_m} [\Phi_{r\alpha} (i_{\beta1} - i_{\beta2}) - \Phi_{r\beta} (i_{a1} + i_{a2})].
\]

(11)

Then, we calculate the speed from the following mechanical equation:

\[
\frac{d\omega_s}{dt} = C_{cm} - C_r - K_r \omega_s.
\]

(12)

Figure 4 illustrates the steps estimation of the rotor speed.

4. Simulation

The control of DSIM by ADRC without current and speed sensors is simulated in Simulink/MATLAB.

To show the efficiency of the proposed method, we perform two tests:

(i) Load variation test.

(ii) Speed inversion test

In both tests, we compare the simulation results of DSIM using the proposed estimators (the model in Figure 2) with the simulations results of DSIM using current and speed sensors (the model in Figure 1).

All parameters of the machine and the gains of its regulators are listed as follows:

(i) Parameters of the DSIM:

Rated power 4.5 kW
Number of pole pairs \( P = 2 \)
Stator and rotor resistors: \( R_s = R_q = 0.86 \Omega, R_r = 0.36 \Omega \)
Stator and rotor inductances: \( L_s = L_q = 0.184 \text{H}, L_r = 0.0246 \text{H} \)
Mutual inductance: \( L_m = 0.0537 \text{H} \)
Moment of inertia: \( J = 0.025 \text{kg.m}^2 \)
Coefficient of friction: $K_f = 0.001 \text{Nms/rad}$

(ii) Parameters of the ADRC regulators of the stator current:

$K_p = 379.1709$, $b_0 = 5.4348$, $\beta_1 = 7.5834e + 03$, and $\beta_2 = 1.4377e + 07$

(iii) Parameters of the PI regulators of the rotor flux

$K_{Pr} = 37.7358$ and $K_{Pr} = 175.0632$

(iv) Parameters of the PI regulators of speed:

$K_{Pw_1} = 1.1865$ and $K_{Pw_1} = 11.8850$

4.1. Load Variation Test. To test the validity and the effectiveness of the proposed estimators against load variation, we implemented the model in Figure 1 and the model in Figure 2 in Simulink and we simulate the two models under the following conditions:

(i) The speed reference is fixed at 100 rad/s
(ii) The flux is kept constant at 1 Wb
(iii) At the start, the machine works empty, and at 1 s, we introduce a load torque of 12 N.m, and then at 3 s the load becomes 18 N.m

4.2. Speed Inversion Test. This test studies the performance of the proposed method against the speed inversion. The two systems are simulated under the following conditions:

(i) The reference speed is fixed at 100 rad/s, and at 3 s the speed is inversed from 100 to $-100$
(ii) The flux is kept constant at 1 Wb
(iii) The machine is running empty

The results of the simulation of two tests are shown in Figures 5–12. It represents the evolutions of the torque, the speed, the flux, and the stator current $i_{s1}$, in the case where we used the measurements of the sensors (Figure 1) and in the case where we used estimated values (Figure 2).

The results of the first test are presented in Figures 5–8. Figure 5 shows the torque variation. The motor start with a zero reference torque, the starting torque using estimated values is about 16 N.m while that of the measured values is about 18 N.m, after 0.25 s, the torque becomes zero. At 1s, we introduce a load torque of 12 N.m, and at 3 s the torque reference was set to 18 N.m, we note that the torque follows their references values.

Figure 6 illustrates the variation of the rotor speed. It can be seen that the speed follows the desired reference with the presence of a small perturbation at 1 s and 3 s, particularly due to the variation of load torque.

We note from Figure 7 that the rotor flux tracks its reference value. The variation of flux by measured and estimated values is superposed.

It is found from Figures 5–7 that the decoupling is done in both cases.

Figure 8 shows the variation of the measured and the estimated values of the stator current $i_{s1}$. We can see that the estimated and the measured values are sinusoidal.
The simulation results of the second test are shown in Figures 9–12.

This test consists of running the machine empty and inversing the speed at 3 s. We note from Figure 9 that the torque is maintained at zero, with the presence of starting torque and disturbance at 3 s due to the inversion of speed.

Figure 10 illustrates the speed variation, we note from this figure that the speed follows its reference even when we inverse the speed reference. The flux in Figure 11 is fixed at 1 Wb. The decoupling is perfect.

From Figure 12, we can see that the stator current is perfectly sinusoidal. At 3 s the current changes its direction due to the inversion of speed.

The variations of all the parameters, when used the measured and the estimated values, are the same and the decoupling is always carried out.

We can conclude that the estimators reduce the starting torque, therefore a further reduced stator current. In addition, we find that the response of the speed is faster when using the model of the machine without current sensors.

Therefore, our estimator is efficient, it can replace the current and speed sensors well.

In comparison with other methods cited in reference [13, 15, and 16]. We note that our method proposes the use of one sensor and the others propose the use of two sensors. The starting torque in reference [15] is very important than that in our method. The speed in [15] has an overtaking but
in our method, it has no overtaking. We conclude that our method is very economical and efficient compared to the other methods [13, 15, 16].

5. Conclusion

In this paper, a control strategy is applied to the double star induction machine without stator current and speed sensors. Current and speed estimators are proposed to avoid the problems affecting the sensors.

The elimination of sensors contributes to lower installation costs. The proposed method has proven its performance and robustness under different simulation conditions. The simulation results have shown that the estimators can well replace the sensors. In applications requiring the use of sensors, these two estimators can be used in a fault-tolerant sensor control block.

Abbreviations

\[ \begin{align*}
V_{\alpha 1}, V_{\beta 2}, V_{\alpha 1}; & \quad \text{Voltages of stator 1} \\
V_{d 1}, V_{d 2}, V_{q 1}; & \quad \text{Voltages of stator 1 and 2 in } d-q \text{ axis, respectively} \\
i_{d 1}, i_{d 2}, i_{q 1}, i_{q 2}; & \quad \text{Measured value of current of stator 1 and 2 in } d-q \text{ axis, respectively} \\
i_{a 1}, i_{a 2}, i_{b 1}, i_{b 2}; & \quad \text{Measured value of current of stator 1 and 2 in } \alpha-\beta \text{ axis, respectively} \\
i_{d 1ES}, i_{d 2ES}, i_{q 1ES}, i_{q 2ES}; & \quad \text{Estimated value of current of stator 1 and 2 in } d-q \text{ axis, respectively} \\
i_{a 1ES}, i_{a 2ES}, i_{b 1ES}, i_{b 2ES}; & \quad \text{Estimated value of current of stator 1 and 2 in } \alpha-\beta \text{ axis, respectively} \\
\psi_r; & \quad \text{Flux of rotor} \\
C_r; & \quad \text{Load torque} \\
R_{S 1}, R_{S 2}; & \quad \text{Stator resistances (stator 1 and 2)} \\
R_; & \quad \text{Rotor resistance} \\
L_{S 1}, L_{S 2}; & \quad \text{Stator self-inductances (stator 1, 2)} \\
L_; & \quad \text{Rotor self-inductance} \\
L_m; & \quad \text{Cyclic mutual inductance between stator 1, stator 2 and rotor} \\
\omega_s; & \quad \text{Stator speed in rad/s} \\
\omega_; & \quad \text{Rotor speed in rad/s.}
\end{align*} \]

Data Availability

All data are available in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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