International Journal of Engineering and Information Systems (IJEAIS)
ISSN: 2643-640X
Vol. 5 Issue 2, February - 2021, Pages: 82-92

Core Loss Compensation of Sensorless Direct-Field Oriented Induction Motor Drives Based on Adaptive Full-Order Observer

Ahmed G. Mahmoud A. Aziz[1*], Yehia Sayed Mohammed[2], Hamdi Ali[3], Ahmed A. Zaki Diab[4]

[1,2,4]Dep. of Electrical Engineering, Faculty of Engineering, Mina University, Minia 61111, Egypt;
[1,3]Dep. of Electrical and Computer Engineering, El_Minia High Institute of Engineering and Technology, Minia 61111, Egypt.
[*]**Correspondence: Ahmed G. Mahmoud A. Aziz,** A.G.mahmoud@mhiet.edu.eg, https://orcid.org/0000-0001-5484-4223

Abstract— *Induction motor (IM) drives, specifically the three-phase IMs, are a nonlinear system that is difficult to explain theoretically due to their sudden changes in speed or load conditions. Thus, advanced controllers are required to boost the IM performance. In many IM applications, vector-control is the most widely used technique owing to its high rendering for controlling IMs. However, there are some issues with this technique when applied in IM drives. This paper introduces a sensorless direct field-oriented control (DFOC) IM drive via adaptive full-order observer (AFOO) taking core-loss in to account. The AFOO is designed to simultaneous estimate of stator and rotor resistance, and rotor speed. Given that there is a noticeable influence of IM core-loss on the sensorless system of IM drives, an approach has been proposed that compensates for the effect of these losses in such a way that it does not affect the estimation of both rotor velocity and motor parameter. Via MATLAB®* **and** *Simulink® from Math Works® (2018a, Natick, MA, 01760-2098 USA) simulation results, the proposed sensorless system can operate at low-speed. Furthermore, a comparison among the conventional FOO (without core-loss compensation) and the suggested one (with core-loss compensation) has been carried out.*

Keywords—induction motor; vector control; sensorless; core loss; observer

1. Introduction

Due to their advantage of easy and precise power and control structures for flux and torque control, electrical direct current (DC) drive systems are quietly used in a wide variety of industrial applications. However, due to corrosion due to friction of the commutator segments and brushes and spark, the DC machines are hard to maintain [1, 3]. The IMs are an important class of electrical machines that are commonly used in industry as a motor and are developed in large quantities as they are widely used in various applications and account for around 60 percent of the total consumption of industrial electricity [2]. Since they are based on the conversion of electricity into mechanical energy (including factories, industrial sectors, air compressors, fans, railway traction systems, pumps, blowers, cranes, textile mills, electrical home appliances, automobiles, transportation modes, and wind generation systems) [1-3].

Control operation in low-speed region is an issue in speed-sensorless drives. The key cause for this is the lower precision of stator voltage measurement in low-speed. Besides, unbalances and offsets in current and voltage add to this problem. A variety of suggested works in this respect have attempted to reduce the issue.

A robust speed-sensorless method is described in [4] for estimating the IM speed throughout measured terminal currents and voltages in vector controlled drive. Instantaneous reactive power measurement is the basis of this methodology. This method is not based on the perception of stator resistance value, nor is it influenced by temperature variations of stator resistance. Furthermore, sensed variables integration is not demand to reduce the computational burden at all. This technique, therefore, could realize quite wider bandwidth speed regulation than prior tacholess drives.

In [5], the H_infinity (H_∞) theory for speed estimation is suggested. The benefit of this suggested work is that the motor assessed speed is utilized as a control signal in a sensor-free FOC mechanism for IM drives and wide speed range is gotten.

In [6], authors suggested a speed observer via ANN method. Through use of ANN for velocity assessment, it made the drive robust and also it can be assumed that the controller does not need precise system knowledge and is thus independent of any variations in motor parameters.

The cost of speed sensor is within the same range as motor price itself, at least for IMs with ratings below 10 kW and also sensor mounting to a motor is a hurdle [5, 7]. Uncertainties of the IM parameter are substantial problematic in vector-control. Sensorless algorithms in IM drives work well in medium and high-speed ranges but lacks accuracy and robustness at low-speeds particularly around zero-excitation frequency. In fact, under low-speed operation, drives become unstable and the torque capability decreases which cause an inaccurate speed control [7]. In addition to the previous problems, iron core-losses of IMs operating on sinusoidal power supply are one of the major losses that represents approximately $15-25\%$ of the overall losses [8]. All these defects have prompted the authors to investigate deeply and thoroughly the transient and steady-state performance of the IM drives taking these limitations into account.

2. ADAPTIVE ROTOR FLUX OBSERVER BASED DIRECT FIELD-ORIENTED CONTROL IM DRIVE

The field angle is measured or calculated from an observer or estimator in the so-called DFOC scheme [2, 9]. On the other hand, the field angle is obtained as equal to the sum of an estimated slip-angle and the rotor position angle in the so-called indirect field-orientation control (IFOC) scheme [10]. However, all the FOC methods suffer from some specific practical problems. In the IFOC method, the slip-angle depends generally on the rotor time-constant value that varies with saturation, temperature and load. The DFOC method that has a minor dependency on rotor parameters, suffer from measured instability of the flux vector at low-speeds at a time where Hall sensors are rarely used in industrial applications. Only estimation or observation of the flux vector is possible with DFOC method and is generally done starting from the machine-terminal variables and using a machine model with related parameters. Fundamental principles of vector-controlled IMs were derived under the assumption that all parameters are constant and the core-loss is neglected [11, 12].

2.1 Dynamic Model of THE IM

Though the dynamic IM performance is well represented in 3-phase model of the IM, it is very multifaceted to appreciate. We supposing to rewrite the following (1)–(4) to describe the IM state-space model (in stationary $(\alpha-\beta)$ reference frame) in terms of equivalent core-loss resistance, R_m that is included in R_{fe} where R_m is presumed to be proportional to $\omega^{1.6}$ [7].

$$p\,i_{\alpha s} = -\left(\frac{R_s}{L_s\,\sigma} + \frac{R_r\,L_m^2}{L_s\,L_r^2\,\sigma}\right) i_{\alpha s} + \left[\frac{R_r\,L_m + R_m(sL_m - L_r)}{L_s\,L_r^2\,\sigma}\right] \Psi_{\alpha r} + \frac{L_m}{L_s\,L_r\,\sigma}\,\omega_r\,\Psi_{\beta r} + \frac{1}{L_s\,\sigma} v_{\alpha s} \tag{1}$$

$$p\,i_{\beta s} = -\left(\frac{R_s}{L_s\,\sigma} + \frac{R_r\,L_m^2}{L_s L_r^2 \sigma}\right) i_{\beta s} + \left[\frac{R_r\,L_m + R_m(sL_m - L_r)}{L_s\,L_r^2\,\sigma}\right] \Psi_{\beta r} - \frac{L_m}{L_s\,L_r\,\sigma}\,\omega_r\,\Psi_{\alpha r} + \frac{1}{L_s \sigma} v_{\beta s} \tag{2}$$

$$p\,\Psi_{\alpha r} = \frac{R_r\,L_m}{L_r}\,i_{\alpha s} - \left(\frac{R_r - s}{L_r}\right)\Psi_{\alpha r} - \omega_r\,\Psi_{\beta r} \tag{3}$$

$$p\,\Psi_{\beta r} = \frac{R_r\,L_m}{L_r}\,i_{\beta s} - \left(\frac{R_r - s}{L_r}\right)\Psi_{\beta r} + \omega_r\,\Psi_{\alpha r} \tag{4}$$

where p is a differential operator; R_{fe} is the equivalent resistance representing the iron losses; R_s, R_r are the stator and rotor resistance, respectively; ω_r is the rotor speed, s is the slip and ω is the excitation frequency.

The electromagnetic-torque can be represented in terms of stator and rotor flux component:

$$T_e = K_t\left(\Psi_{\alpha r}\;i_{\beta s} - \Psi_{\beta r}\,i_{\alpha s}\right) \tag{5}$$

where, $K_t = \frac{3PL_m}{2L_r}$ and P is the pole-pairs

2.2 Adaptive Full Order Observer with Core-loss Compensation

In the FOC schemes, the detection of rotor speed is necessary for calculating the field angle and adjustment of the speed in a feedback-loop. However, the speed sensor spoils the ruggedness and simplicity of the IMs, so that the elimination of this sensor has been one of the important requirements in vector-control schemes. Many investigations about speed-sensorless vector-controlled IM drives were reported [5, 7, 9], but little attention was paid to the effect of core-loss on motor performance. The core-loss is considered as one of the sources of detuned operation of vector-controlled IMs. This motivated the authors to investigate how significant is the effect of core-loss on speed-sensorless DFOC of IMs.

In this work, accurate state estimation is a major step towards achieving good performance of MPTFC in dynamic implementation. Owing to its precision and insensitivity to parameter variance over a broad speed range [7, 9], AFOO is approved for rotor speed-flux estimation. By compensating for the impact of core-loss, AFOO mathematical model can be revealed as [9]:

$$p\,\hat{x} = \hat{A}\,\hat{x} + B\,v_s + H\,(\hat{\imath}_s - i_s) + D\,\hat{\Psi}_r \tag{6}$$

where $\hat{x} = [\hat{i}_s\ \hat{\Psi}_r]^T$ is the estimated state for stator current and rotor flux, v_s is stator voltage vector, $I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, $B = [\frac{1}{L_s\sigma} I\ 0\ ]^T$, [D] is the core-loss compensating term,

$\hat{A} = \begin{bmatrix} \hat{A}_{11} & \hat{A}_{12} \\ \hat{A}_{21} & \hat{A}_{22} \end{bmatrix} = \begin{bmatrix} -\left(\frac{\hat{R}_s}{L_s\sigma} + \frac{\hat{R}_r L_m^2}{L_s L_r^2 \sigma}\right) I & \frac{L_m}{L_s L_r \sigma}\left(\frac{\hat{R}_r}{L_r} I - \hat{\omega}_r J\right) \\ \frac{\hat{R}_r L_m}{L_r} I & -\frac{\hat{R}_r}{L_r} I + \hat{\omega}_r J \end{bmatrix}$, $D = \begin{bmatrix} D_1\ I \\ D_2\ I \end{bmatrix} = R_m \left[-\frac{(L_r - s\ L_m)}{(\sigma L_s {L_r}^2)} I \quad -\frac{s}{L_r} I \right]^T$ and the observer gain matrix is given as:

$$H = \begin{bmatrix} h1 & h2 & h3 & h4 \\ -h2 & h1 & -h4 & h3 \end{bmatrix}^T \tag{7}$$

For simplicity, feedback gains being given in our study as:

$$\begin{cases} h_1 = h_3 = 0.052 \\ h_2 = \dfrac{-L_r(h_1 - h_3 + R_s)}{R_r} \omega_r \\ h_4 = 0 \end{cases} \tag{8}$$

Via applying Lyapunov's theorem in order to deriving the AFOO stability, the estimate error of the stator current, and rotor flux (based on (1-4), (6)) is described as:

$$p.e = (A + HC).e - \Delta A \hat{x} \tag{9}$$

where $e = x - \hat{x}$, $\Delta A = \hat{A} - A = \begin{bmatrix} 0 & -\Delta\omega_r J/c \\ 0 & \Delta\omega_r J \end{bmatrix}$, $c = (\sigma L_s L_r)/L_m$ and $\Delta\omega_r = \hat{\omega}_r - \omega_r$.
The following Lyapunov function applicant can be defined as:

$$V = e^T.e + (\hat{\omega}_r - \omega_r)^2/\xi \tag{10}$$

where ξ is an arbitrary positive constant, then time derivative of V becomes:

$$\begin{aligned} p.V = e^T\{(A + HC)^2 + (A + HC)\}.e - 2\Delta\omega_r(e_{is\alpha}\hat{\Psi}_{\beta r} - e_{is\beta}\hat{\Psi}_{\alpha r})/c \\ + \quad 2\Delta\omega_r p\hat{\omega}_r/\xi \end{aligned} \tag{11}$$

where $e_{i\alpha s} = i_{\alpha s} - \hat{\iota}_{\alpha s}$, $e_{i\beta s} = i_{\beta s} - \hat{\iota}_{\beta s}$.

2.2.1 Rotor Speed Estimation

The suggested scheme is seen in Fig. 1. The adaptive closed-loop provides the rotor velocity $\hat{\omega}_r$, calculated on the basis of difference among estimated and measured currents ($e_{i\alpha s}$ and $e_{i\beta s}$) multiplied by estimated rotor flux $\hat{\Psi}_r$ as per as (6).

Subsequently, the rotor speed could be estimated according to Lyapunov's theory as [9]:

$$\begin{cases} e_\omega = e_{i\alpha s}\hat{\Psi}_{\alpha r} - e_{i\beta s}\hat{\Psi}_{\beta r} \\ \hat{\omega}_r = \left(K_{p\omega} + \dfrac{K_{i\omega}}{s}\right).e_\omega \end{cases} \tag{12}$$

where $K_{p\omega}$, $K_{i\omega}$ are the PI gains of the estimated rotor speed, and $(1/s)$ is an integral operator.

2.2.2 Stator And Rotor Resistance Estimate

The major issue arising in IM drives is the calculation of motor parameters. Via the blocked rotor test and DC-test, the motor parameters could be determined easily. However while operation, motor parameters change with frequency, load disturbances and rise in temperature. Motor Inductances varies with the magnetic material saturation, while resistances changes with temperature.

Rendering to the same Lyapunov's theory, stator resistance R_s can also be estimated like rotor velocity via a PI controller [7, 12].

International Journal of Engineering and Information Systems (IJEAIS)
ISSN: 2643-640X
Vol. 5 Issue 2, February - 2021, Pages: 82-92

$$\begin{cases} e_{R_s} = e_{i\alpha s}\,\hat{i}_{\alpha s} + e_{i\beta s}\,\hat{i}_{\beta s} \\ \hat{R}_s = \left(K_{pR_s} + \dfrac{K_{iR_s}}{s}\right).\,e_{R_s} \end{cases} \quad (12)$$

Furthermore, stator current and rotor flux error estimation can give rotor resistance estimate utilizing Lyapunov theory throughout the suggested AFOO in (6) as:

$$\begin{cases} e_{R_r} = \begin{Bmatrix} e_{i\alpha s}\left(\hat{\Psi}_{\alpha r} - L_m\,\hat{i}_{\alpha s}\right) + \\ e_{i\beta s}\left(\hat{\Psi}_{\beta r} - L_m\,\hat{i}_{\beta s}\right) \end{Bmatrix} \\ \hat{R}_r = \left(K_{pR_r} + \dfrac{K_{iR_r}}{s}\right).\,e_{R_r} \end{cases} \quad (13)$$

where K_{pR_s}, K_{iR_s}, K_{pR_r}, and K_{iR_r} are PI gains of the stator and rotor resistance, respectively.

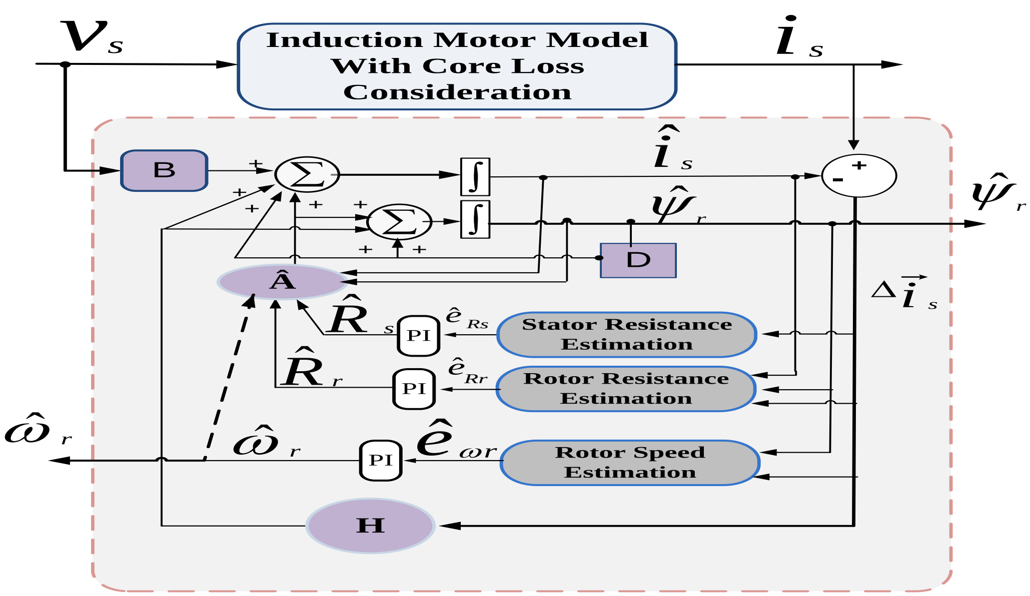

Fig. 1. *Block diagram of sensorless AFOO with core-loss compensation.*

3. THE SUGGESTED SENSORLESS DIRECT FIELD-ORIENTED IM DRIVE LAYOUT

The complete block diagram of the proposed sensorless DFOC of an IM drive is presented in Fig. 2. The sensorless system consists mainly of IM model with core-loss consideration, a hysteresis current-controlled pulse-width modulated (CR PWM) inverter, and AFOO (with core-loss compensation). The stator voltages and currents are the measured quantities that used by proposed sensorless AFOO to obtain the estimated values of rotor velocity ($\hat{\omega}_r$) and rotor flux($\hat{\Psi}_r$). Estimated states are fed back toward the outer-loops of both rotor flux and rotor velocity.

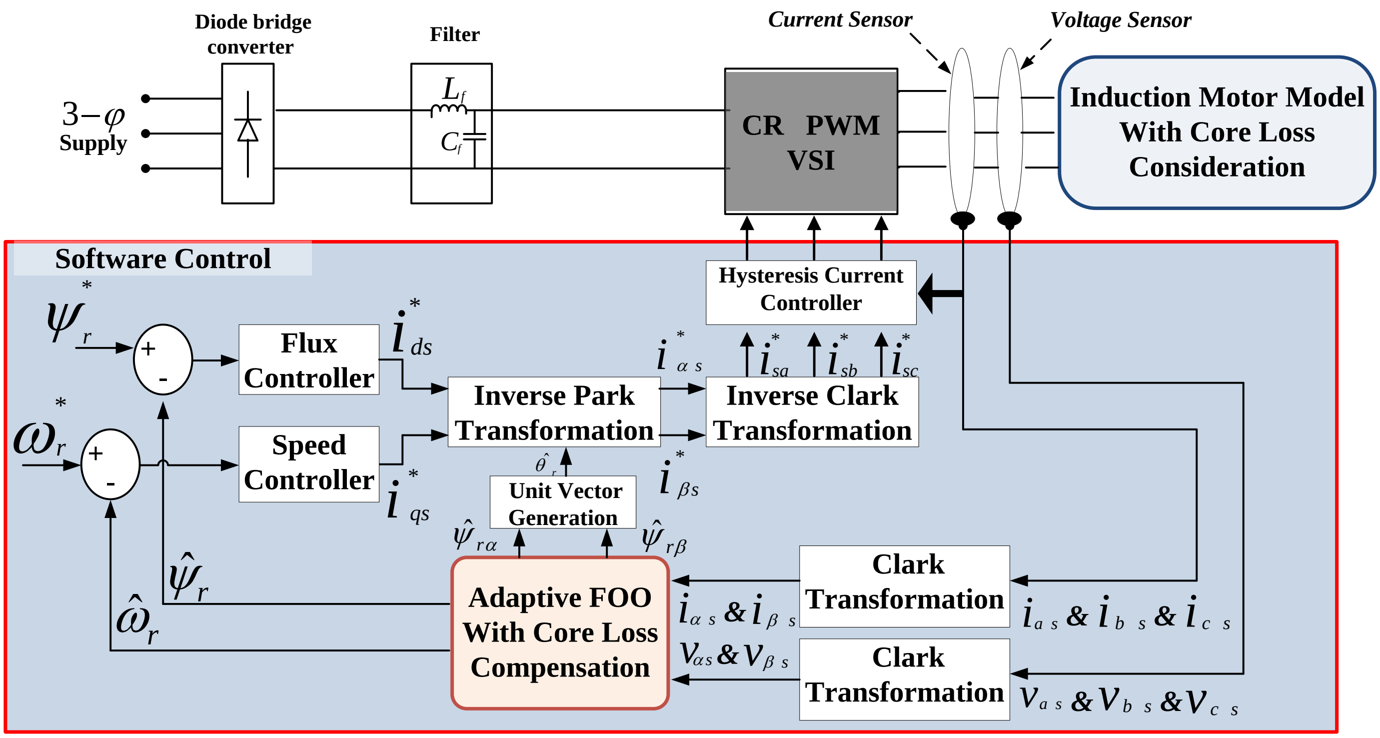

Fig. 2. *Sensorless DFOC of IM drive based on AFOO with core-loss consideration.*

4. Using the Template

The effectiveness of the sensorless DFOC of an IM drive that suggested in this work is verified via MATLAB® and Simulink® environment. The parameters Motor parameters are mentioned in Table 1. To validate the suggested sensorless DFOC of an IM drive, the following cases is assumed.

4.1 Case A

The load-torque is held constant at (4 Nm) during the whole test period and nominal motor parameter are assumed. The timing sequence, as shown in Fig. 3, as following, At (t = 0.5 sec.) the motor is started, during (1 sec.) reference speed is increased linearly up to (200 rpm), and kept constant for (2 sec.), at (t = 3.5 sec.) reference speed decreases linearly up to (0 rpm). This results show that, the reference, estimate and actual velocities are nearly aligned. Furthermore, the actual velocity could track the reference speed trajectory. The estimate d-axis flux-component is constant (at rated rotor flux 0.8 wb) and the estimate q-axis flux-component nearly equal zero. The assessment values of both stator and rotor resistance have nearly the same values of its actual values.

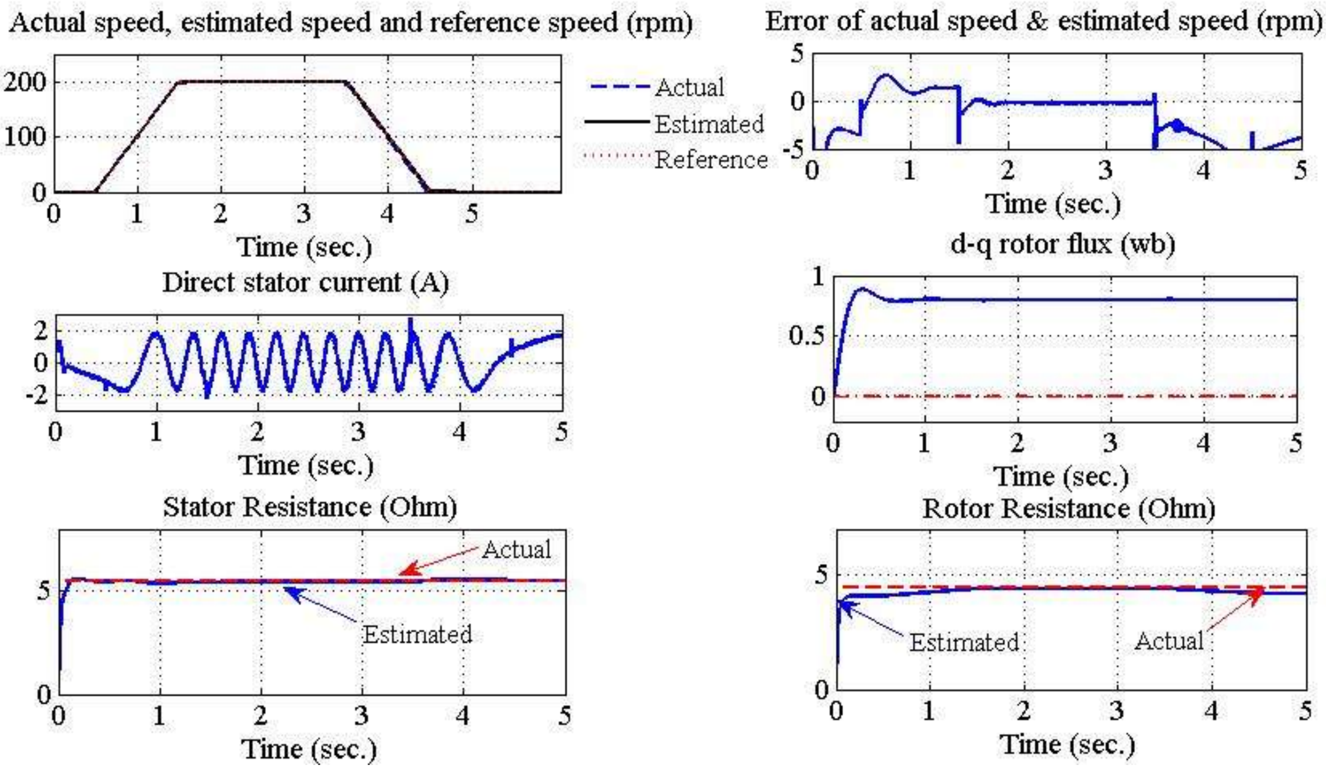

Fig. 3. *Performance of sensorless DFOC IM drive at low-speed operation based on AFOO.*

4.2 Case B

Figure 4 shows the suggested sensorless system performance throughout speed reversals (four quadrants). The reference velocity is increased linearly up from (0 rpm) at (t = 0.5 sec.) to (+100 rpm) in (1 sec.), and kept constant for (1 sec.), at (t = 2.5 sec.) reference speed decreases linearly up to (-100 rpm) in (1 sec.) and kept constant for (1 sec.), at (t = 3.5 sec.) the reference speed goes to (0 rpm) in (1 sec.). This case shows a good dynamic performance of the suggested sensorless system under speed-reversal operation. However, the error among actual and estimate velocity is relatively high. Stator current is nearly sinusoidal and also stable at the speed reverse peed-reversal operation. An acceptable estimate of stator and rotor resistances is obtained as shown.

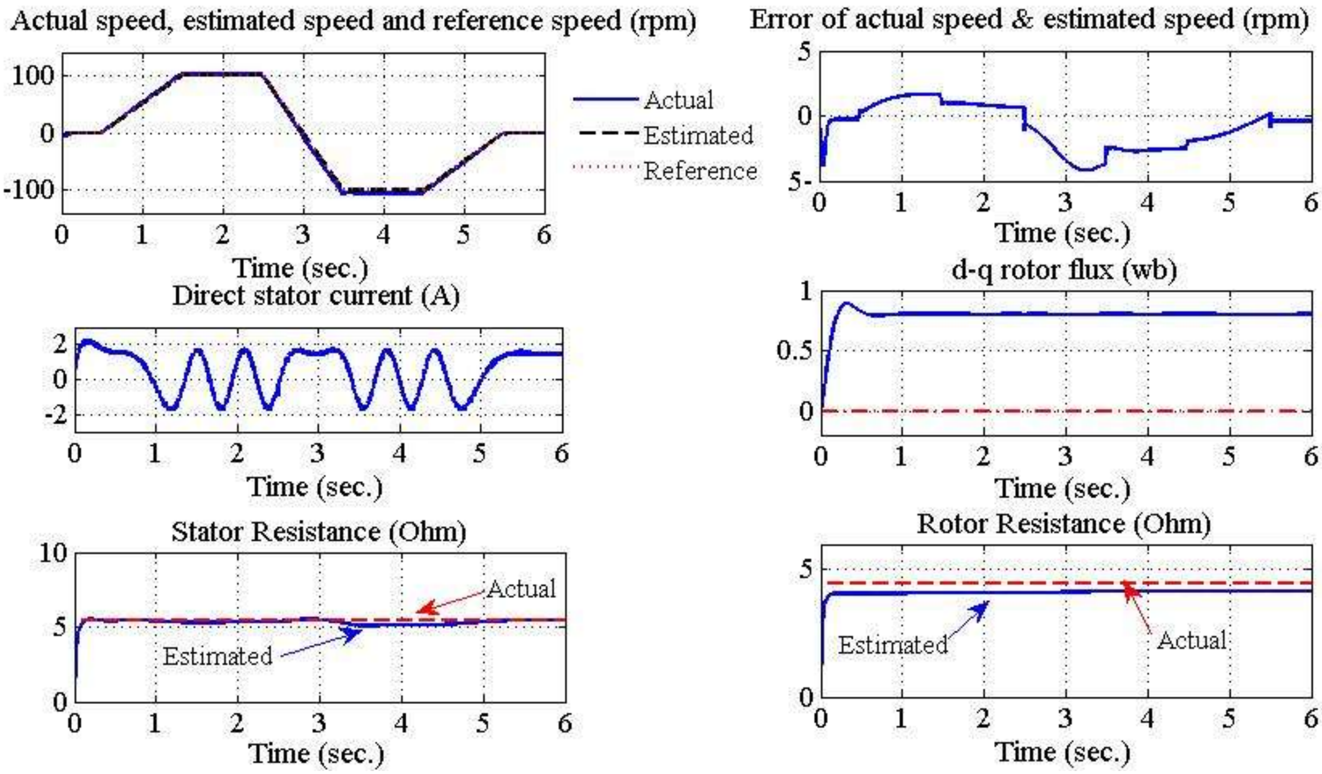

Fig. 4. *Performance of sensorless DFOC IM drive under reversal-speed operation based on AFOO.*

4.3 Case C

The suggested sensorless system performance is tested (in this case) under both stator and rotor resistance variation. The load-torque is held constant at (2 Nm) during the whole test period and reference velocity is increased linearly up from (0 rpm) at (t = 0 sec.) to (100 rpm) in (1.5 sec.). As stator resistance variation is a significant issue in DFOC method, stator resistance increase will be tested twice to test the suggested system durability. Stator resistance is increased linearly up to (2 R_s) in (2 sec.), and kept constant for (1 sec.), at (t = 5 sec.) stator resistance increases suddenly up to ($3R_s$). Also step change to rotor resistance at (t=5 sec.) from (R_r) to ($2R_r$) is applied.

At the resistance variation instant, an undesirable dip in rotor velocity, however, the restoring time of this dip occurs in a short time as the estimate rotor flux rises to compensate the excess in voltage drop in stator windings. Figure 5 also show a robust flux response at low-speed when stator and rotor resistance is increased. Motor torque has a large pulsation that comes from CR PWM inverter and also resistance variations. Stator and rotor resistance estimation track their actual values well.

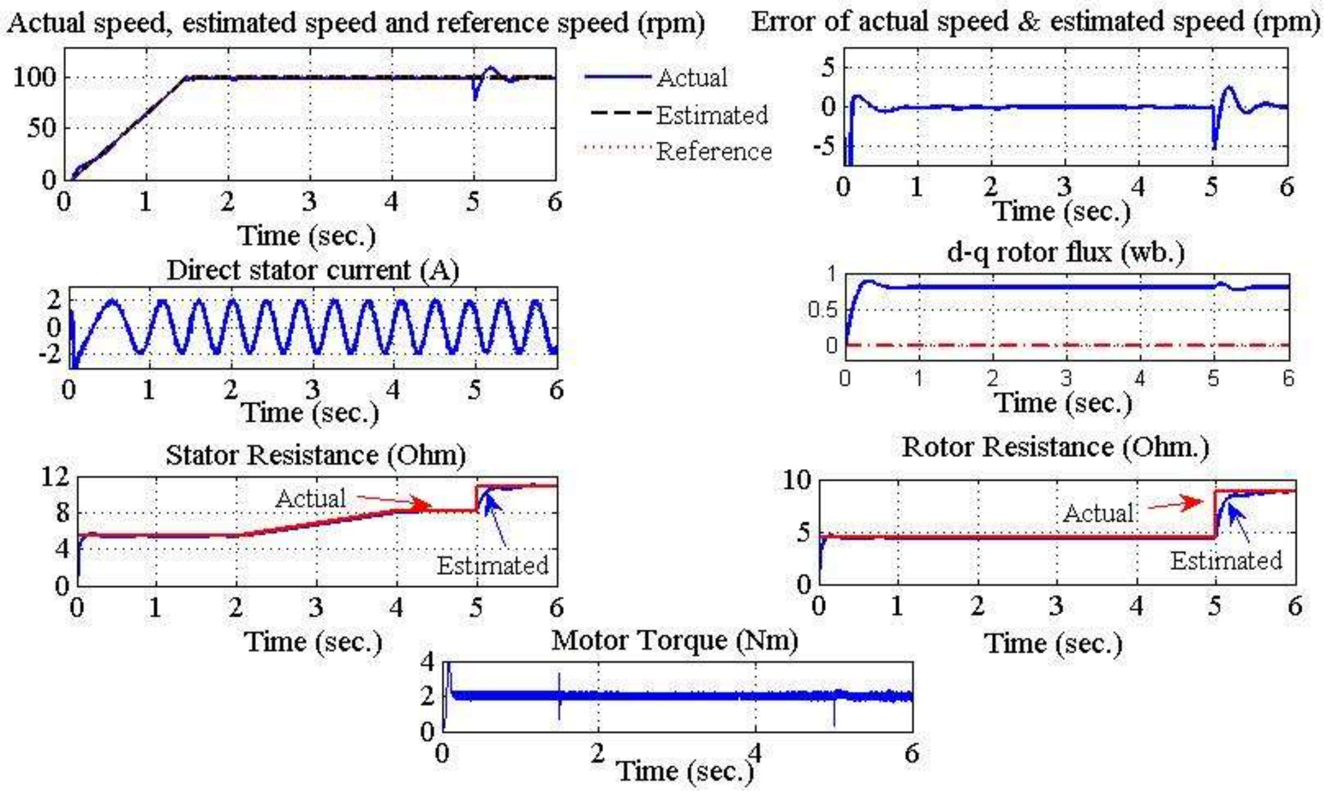

Fig. 5. *Effect of stator and rotor resistance variation on sensorless DFOC IM drive based on AFOO.*

4.4 Case D

Furthermore, the suggested sensorless drive performance under step change of load-disturbance is shown in Fig. 6 at low-speed operating range of (100 rpm) with nominal motor parameter. A load-torque of (2 Nm) is applied at starting, then load torque is increased to (7 Nm) at (t=2 sec.) then finally back to (4 Nm) at (t=5 sec.). A good dynamic performance has been obtained. Moreover, acceptable estimation of stator, rotor resistance and speed has been shown in Fig. 6. Actual value of rotor flux is very robust in the suggested drive, as it is compensated by the estimated rotor flux value, as shown in Fig. 6. Moreover, the error among actual and estimate velocity could be seen as a rather good feature, demonstrating high robustness against external load-disturbance of the proposed DFOC IM drive. In addition to acceptable assessment of stator and rotor resistance is gotten.

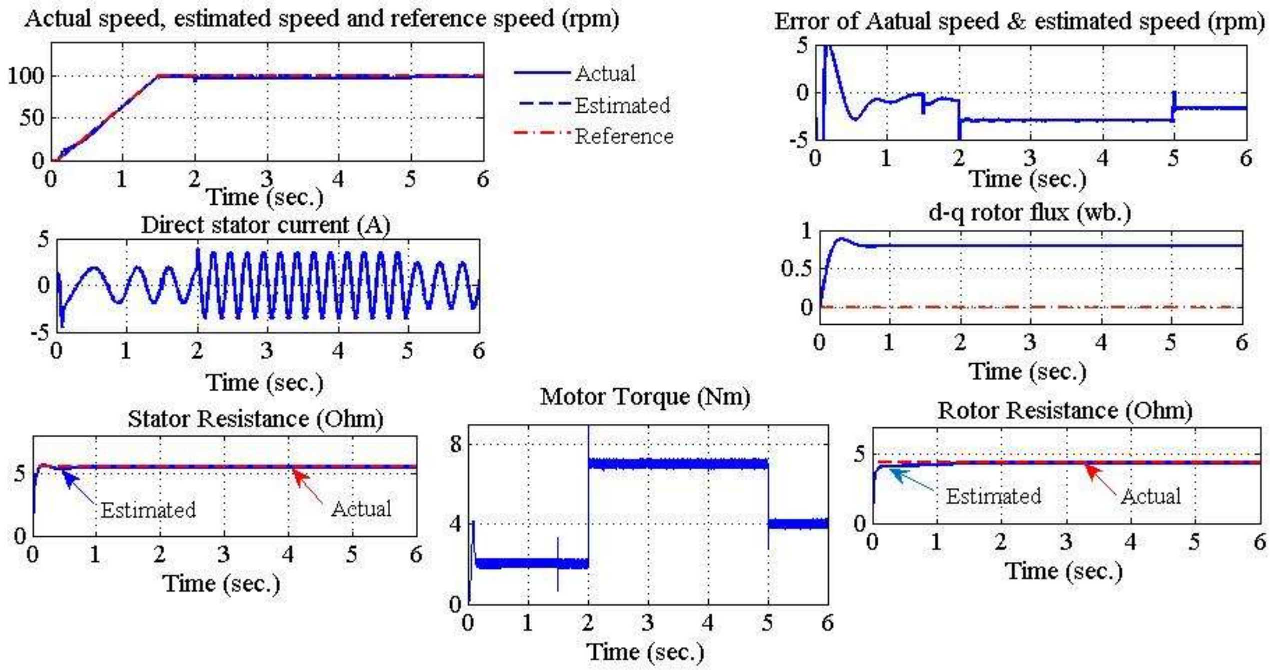

Fig. 6. *Performance of sensorless DFOC IM drive at load-disturbance based on AFOO.*

4.5 Case F

The core-loss influence on the actual and estimate quantities of both rotor velocity and motor resistance is presented in Fig. 7. The suggested sensorless DFOC IM drive (with core-loss compensation) gives higher dynamic- performance over the traditional one (without core-loss compensation), as shown in Fig. 7.

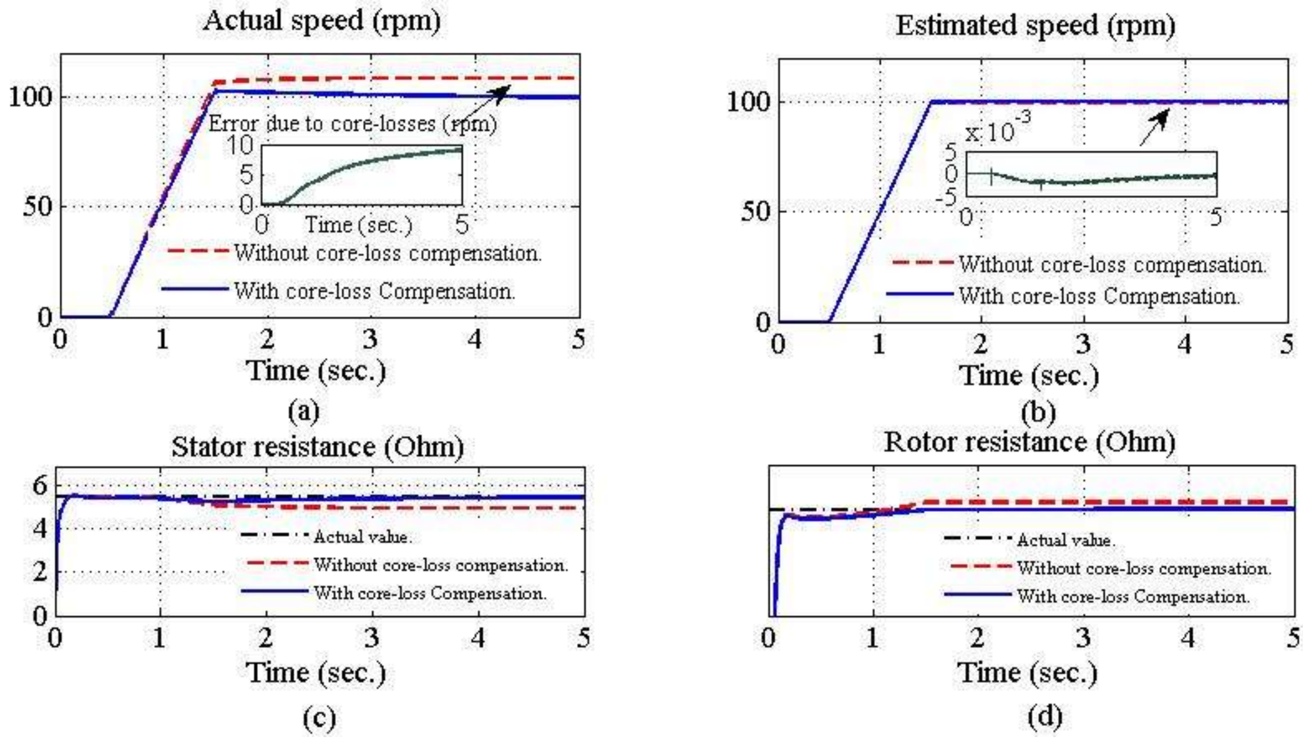

Fig. 7. *Performance of the suggested sensorless DFOC IM drive based on AFOO taking core-loss influence and its compensation in to account on: (a) Actual rotor velocity. (b) Estimate rotor velocity. (c) Stator resistance. (d) Rotor resistance.*

Table 1. IM Parameter.

Symbol	Parameters	Values
v_s	Rated voltage	380 V
n_p	No. pole pairs	2
f	Rated frequency	50 Hz
P_r	Rated output-power	1.1 Kw
I_{Sn}	Rated current	2.77 A
R_s	Stator resistance	5.46 Ω
R_r	Rotor resistance	4.45 Ω
L_s	Stator self-inductance	0.492 H
L_r	Rotor self-inductance	0.492 H
L_m	Magnetizing inductance	0.475 H
J	Moment of inertia	0.005 Kgm^2
Ψ_{rn}	Nominal rotor flux	0.8 wb
T_n	Nominal torque	7 Nm
R_m	Core-resistance	2 KΩ

5. Acknowledgment

A sensorless DFOC of an IM drive is suggested in the present study based on AFOO taking core-loss into account. A new design for sensorless AFOO (with core-loss compensation) has been suggested. Moreover, a comparison among the conventional AFOO (without core-loss compensation) and the suggested one (with core-loss compensation) has been made. The presented results prove the effectiveness of the suggested sensorless DFOC of an IM drive with respect to the estimate quantities of both motor parameters and velocity.

6. References

[1] B. Wu and M. Narimani, *High-power converters and AC drives*. John Wiley & Sons, 2017.

[2] A. A. Z. Diab, A.-H. M. Al-Sayed, H. H. Abbas Mohammed, and Y. S. Mohammed, "Literature Review of Induction Motor Drives," in *Development of Adaptive Speed Observers for Induction Machine System Stabilization*Singapore: Springer Singapore, 2020, pp. 7-18.

[3] C. M. F. S. Reza, M. D. Islam, and S. Mekhilef, "A review of reliable and energy efficient direct torque controlled induction motor drives," *Renewable and Sustainable Energy Reviews,* vol. 37, pp. 919-932, 2014.

[4] P. Fang-Zheng and T. Fukao, "Robust speed identification for speed-sensorless vector control of induction motors," *IEEE Transactions on Industry Applications,* vol. 30, no. 5, pp. 1234-1240, 1994.

[5] A. A. Z. Diab, A.-H. M. El-Sayed, H. H. Abbas, and M. A. Sattar, "Robust Speed Controller Design Using H_infinity Theory for High-Performance Sensorless Induction Motor Drives," *Energies,* vol. 12, no. 5, 2019.

[6] A. Devanshu, M. Singh, and N. Kumar, "Nonlinear flux observer-based feedback linearisation control of IM drives with ANN speed and flux controller," *International Journal of Electronics*, vol. 108, no. 1, pp. 139-161, 2021.

[7] A. G. M. A. Aziz, H. Rez, and A. A. Z. Diab, "Robust Sensorless Model-Predictive Torque Flux Control for High-Performance Induction Motor Drives," Mathematics, vol. 9, no. 4, 2021.

[8] B. A. Nasir, "An Accurate Iron Core Loss Model in Equivalent Circuit of Induction Machines," *Journal of Energy,* vol. 2020, 2020.

[9] A. G. M. A. Aziz, A. A. Z. Diab, and M. A. E. Sattar, "Speed sensorless vector controlled induction motor drive based stator and rotor resistances estimation taking core losses into account," in 2017 Nineteenth International Middle East Power Systems Conference (MEPCON), 2017, pp. 1059-1068.

[10] L. Amezquita-Brooks, J. Liceaga-Castro, and E. Liceaga-Castro, "Speed and Position Controllers Using Indirect Field-Oriented Control: A Classical Control Approach," *IEEE Transactions on Industrial Electronics,* vol. 61, no. 4, pp. 1928-1943, 2014.

[11] D. Arun Dominic and T. R. Chelliah, "Analysis of field-oriented controlled induction motor drives under sensor faults and an overview of sensorless schemes," *ISA Transactions,* vol. 53, no. 5, pp. 1680-1694, 2014.

[12] Y. Wang, J. Yang, S. Li, G. Yang, R. Deng, and H. Hussain, "Multiplane Rotor Resistance Online Estimation Strategy for Multiphase Induction Machine under Non-Sinusoidal Power Supply," *IEEE Transactions on Power Electronics,* pp. 1-1, 2021.