Research Article

Active Disturbance Rejection Control for a Five-Level Cascaded H-Bridge Inverter Fed Induction Motor Sensorless Field-Oriented

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In this paper, a robust vector control sensorless based on three Active Disturbance Rejection Controllers (ADRC) for an induction motor fed by a five-level cascaded H-bridge was developed. The estimation of rotor position is achieved using a Luenberger estimator. The proposed model considers the disturbances and the inaccuracies of the system and compensates them using the extended state observer of ADRC. Moreover, a five-level cascaded H-bridge inverter is the best topology to minimize the torque ripples and to improve the current output of IM under control. The suggested control system was simulated under different conditions using MATLAB-Simulink. The results demonstrate the effectiveness and the robustness of the proposed system against disturbances such as variations of parameters and load torque.

1. Introduction

Induction Motors are widely used in different industrial applications, especially in the variable speed drive applications [1], due to their robustness, high reliability, high performance, and low cost. However, the main problem of Induction Motors is related to the need for a more complex system in its control and because of nonlinear coupling between torque and flux [2].

For this reason, there are various speed control techniques available for the induction engine to solve this decoupling issue [3, 4]. Among all methods, indirect vector control or IFOC is the most popular for achieving high efficiency [5, 6]. Despite its safety and efficacy, IFOC has got several drawbacks such as high torque ripple, an increase in current harmonic distortion, and more disturbance problems. These disturbances can cause several problems for electrical equipment such as intense heating, abrupt shutdown of the induction motor, or even complete loss of this machinery [7].

Recently, due to their numerous benefits against the conventional two-level inverters and increasingly improved performance of the system [8], there has been an increasing

interest in multilevel inverters to feed induction motor in vector control [9]. Five-level inverters (FLIs) are known for the possibility of generating five numbers of levels at the output [10]. As a result, they provide an output quasi-sinusoidal voltage with an improved harmonics spectrum. Albeit various topologies of the FLI in the literature, such as flying capacitor topology and neutral point clamped and cascaded H-bridge (HBCI) [11], the HBCI has the most potential and is used in different applications compared to other multilevel structures [12, 13]. It has a modular structure [14].

The vector control based FL-HBCI offers a better speed response and phase current [15]. It improves the torque ripples performance [16].

Nowadays, researchers have shown an increased interest in sensorless-speed controls [17] because the speed sensor is expensive and because they make control systems much more reliable, durable, robust, and cheaper. For example, they can function effectively against the variations of the machine resistances [18]. Therefore, it is necessary to have an estimator to estimate and to know the speed of the motor. For that, the common techniques to restore speed position are Model Reference Adaptive System, Fuzzy Sliding Mode

Observer, Extended Kalman Filter, and Luenberger Observer (LO) [19]. In this study, the indirect vector control is developed for induction motor fed by FL-HBCI, using LO to estimate the speed position.

Proportional–integral (PI) is a conventional regulator used in different industrial applications, especially applications of induction motor drives, because of its easy implementation and simple structure [20]. However, the performance of the PI controller-based-control system suffers from various problems: perceptual high sensitivity against disturbing and loud noises and the excessive loss of efficiency due to superficial regulation [21]. Moreover, it requires a long recovery period when disturbances occur [22].

In order to overcome these drawbacks, researchers developed a very robust controller called Active Disturbance Rejection Controller (ADRC). It was firstly proposed in 1998 by Han [23] and was later developed by Gao and many researchers [20, 24]. It can reduce output noise and problems due to parameter uncertainty and disturbances. It can improve the robustness of the system against external disturbances and changes in parameters [25, 26]. For that, the PI controllers could be replaced by the ADRC controllers.

The major contribution of this paper is connected to suggesting a robust vector control sensorless system based on three Active Disturbance Rejection Controllers (ADRC) for an induction motor fed by a five-level cascaded H-bridge. The speed estimator is based on Luenberger Observer. To achieve good robustness, the accuracy and the rapidity of responses are expected.

A comparative study is provided with the PI controller applied for FL-HBCI, the simulation results are obtained using MATLAB-Simulink, to verify the performance, to evaluate the robustness of the suggested system, and to investigate its efficiency under different conditions.

The overall structure of the paper takes the form of six sections, including this introductory section. Section 2 is devoted to the models used in this study. Section 3 presents the adaptive scheme for the Luenberger estimator. Section 4 presents the motor commands, focusing on the application of the ADRC controller to the FLI-HBC scheme feeding sensorless-speed. Section 5 presents and discusses the results of the current study. The last section draws conclusions from the study.

2. Models of the System

2.1. Model of Induction Motor. The magnetizing flux equations of an induction motor in a reference two-phase frame (d, q) are shown:

$$\begin{cases} \frac{d\phi_{dr}}{dt} = \frac{L_m}{L_r} R_r i_{ds} - \frac{R_r}{L_r} \phi_{dr} + (\omega_s - \omega) \phi_{qr}, \\ \frac{d\phi_{qr}}{dt} = \frac{L_m}{L_r} R_r i_{qs} - \frac{R_r}{L_r} \phi_{qr} + (\omega - \omega_s) \phi_{dr}. \end{cases} \quad (1)$$

The stator currents of the induction motor in two-phase voltage (V_{ds}, V_{qs}) can be written as follows:

$$\frac{di_{ds}}{dt} = -\left(\frac{1}{T_s \sigma}\right) i_{ds} - \left(\frac{L_m}{L_r L_s \sigma}\right) \frac{d\phi_r}{dt} + \left(\frac{1}{L_s \sigma}\right) V_{ds}, \quad (2)$$

$$\frac{di_{qs}}{dt} = -\left(\frac{1}{T_s \sigma}\right) i_{qs} - \left(\frac{L_m \omega_s}{L_r L_s \sigma}\right) \phi_r + \left(\frac{1}{L_s \sigma}\right) V_{qs}, \quad (3)$$

where

$$\begin{aligned} T_s &= \frac{L_s}{R_s}, \\ \sigma &= 1 - \frac{L_m^2}{L_r L_s}. \end{aligned} \quad (4)$$

The electromagnetic torque (C_{elm}) and the rotor speed (Ω) of the induction motor in the ($d-q$) axis are given as follows:

$$\frac{d\Omega}{dt} = -\left(\frac{f_r}{J}\right) \Omega - \left(\frac{1}{J}\right) C_r + \frac{1}{J} C_{elm}, \quad (5)$$

$$C_{elm} = p \frac{L_m}{L_r} (\phi_{rd} i_{qs} - i_{ds} \phi_{rq}), \quad (6)$$

where ϕ_r is the rotor flux magnitude, p is the number of poles, i_{ds}, i_{qs} are stator current of d and q axis, J is the moment of inertia, ω_s is the synchronous speed, and C_r (Nm) is the load torque.

2.2. Model of Indirect-Field-Oriented Control. The model of indirect vector control was initially invented by Blaschke in 1972 [27]. It is based on decoupling control.

Clarke transformation and Park transformation are used to achieve the DC machine output required [3].

For decoupling control, the fluxes equations are given by

$$\begin{cases} \phi_{dr} = \phi_r = cte, \\ \phi_{qr} = 0. \end{cases} \quad (7)$$

Equations (1) and (6) become

$$\begin{cases} \phi_r = L_m i_{ds}, \\ C_{elm} = K i_{qs}. \end{cases} \quad (8)$$

While $K = p(L_m/L_r)\phi_r = cte$, L_m is mutual inductance.

2.3. FL-HBCI Topology. FLIs perform better than the three-level and the two-level inverters. They provide a harmonic reduction and decrease the losses for motor drives [28].

There are different structures of the FLI, but the HBCI is the preferable one due to its several advantages over other FLIs. It does not need many components, and it does not have fluctuation in neutral point voltage problems compared to FL-Diode Clamped and FL-flying capacitors inverters [29].

A FL-HBCI simplified circuit is presented in Figure 1. It has a modular structure. It comprises two separate DC voltages (T) in every phase; five output voltage levels can be obtained $+2T, +T, 0, -T$, and $-2T$.

The HCB-FLI produces an output voltage equal to $+2T$ when O_3, O_2, O_7 , and O_6 are switched ON. $+T$ can be obtained when O_3, O_2, O_7 , and O_8 are switched ON, whereas 0 can be attained when O_3, O_2, O_8 , and O_5 are on ON. $-T$ can be obtained when O_3, O_8, O_5 , and O_4 are switched ON. $-2T$ can be achieved when O_8, O_5, O_4 , and O_1 are turned ON.

In-phase disposition Sinusoidal pulse-width modulation (IP-SPWM), where all carrier waveforms are in phase, is used to select the switches of the inverter. Its principle is based on the intersection of the sinusoidal reference signal with the triangular carrier waves.

3. Adaptive Scheme for Luenberger Estimator

There are different types of strategies to estimate the parameters of an IM. The Luenberger Observer (LO) is the most popular one due to its simplicity and precision [30].

The principle of the LO method is based on the state-variables model of the induction motor. The measured values (stator voltage and currents) are compared to the estimated values to obtain errors by using an adaptive model. Then, the output error is multiplied by the PI controller to generate the estimated speed.

The LO is designed as follows:

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}), \\ \hat{y} = C\hat{x}, \end{cases} \quad (9)$$

where L is the Luenberger gain.

However,

$$\begin{aligned} \hat{x} &= \begin{pmatrix} \hat{i}_{\alpha s} & \hat{i}_{\beta s} & \hat{\varphi}_{\alpha r} & \hat{\varphi}_{\beta r} \end{pmatrix}^T, \\ \hat{y} &= \begin{pmatrix} \hat{i}_{\alpha s} & \hat{i}_{\beta s} \end{pmatrix}, \\ A &= \begin{pmatrix} p_{11} & 0 & p_{13} & p_{14}\omega_r \\ 0 & p_{11} & p_{14}\omega_r & p_{13} \\ p_{31} & 0 & p_{33} & -\omega_r \\ 0 & p_{31} & \omega_r & p_{33} \end{pmatrix}, \\ B &= \begin{pmatrix} b_{11} & 0 & 0 & 0 \\ 0 & b_{11} & 0 & 0 \end{pmatrix}, \\ C &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}, \\ L &= \begin{pmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} \\ -\lambda_{12} & \lambda_{11} & -\lambda_{14} & \lambda_{13} \end{pmatrix}, \end{aligned} \quad (10)$$

with

$$\begin{aligned} p_{11} &= -\frac{1}{\sigma} \left(\frac{1}{T_s} + \frac{1-\sigma}{T_r} \right), \\ p_{13} &= \frac{L_m}{\sigma L_r L_s T_r}, \\ p_{14} &= \frac{L_m}{\sigma L_s L_r}, \\ p_{31} &= \frac{L_m}{T_r}, \\ p_{33} &= -\frac{1}{T_r}, \\ b_{11} &= \frac{1}{\sigma L_s}, \\ T_r &= \frac{L_r}{R_r}, \\ \sigma &= 1 - \frac{L_m^2}{L_r L_s}, \\ \lambda_{11} &= (1-k)(p_{11} + p_{33}), \\ \lambda_{12} &= (1-k)\omega_r, \\ \lambda_{13} &= (1-k^2) \left(p_{31} + \frac{p_{11}}{p_{14}} \right) - \frac{\lambda_{11}}{p_{14}}, \\ \lambda_{14} &= \frac{\omega_r(1-k)}{p_{14}}. \end{aligned} \quad (11)$$

To ensure stability, the Lyapunov function is used and given by [31]

$$V = e^T e + \frac{(\Delta\omega_r)^2}{\rho}, \quad (12)$$

with ρ being a positive constant coefficient. $e = x - \hat{x}$ is the estimation error vector of the induction motor and LO.

$$\Delta\omega = \omega_r - \hat{\omega}_r. \quad (13)$$

The time derivate of V is expressed as

$$\frac{dV}{dt} = \frac{de^T}{dt} e + e^T \frac{de}{dt} + \frac{1}{\rho} \frac{d(\Delta\omega_r)^2}{dt}, \quad (14)$$

which should be negative.

Thus, equation (14) is developed as [31]

$$\frac{dV}{dt} = e^T \left[(A - LC)^T + (A - LC) \right] e + 2\Delta\omega_r p_{14} (e_{\alpha s} \hat{\varphi}_{\beta r} - e_{\beta s} \hat{\varphi}_{\alpha r}) - \frac{2\Delta\omega_r}{\rho} \frac{d\hat{\omega}_r}{dt}, \quad (15)$$

where

$$\begin{aligned} e_{\alpha s} &= i_{\alpha s} - \hat{i}_{\alpha s}, \\ e_{\beta s} &= i_{\beta s} - \hat{i}_{\beta s}. \end{aligned} \quad (16)$$

The expression $e^T[(A - LC)^T + (A - LC)]e$ is always negative (since the imposed eigenvalues of the LO) [31].

The last two terms can be set to zero because they are weak compared to the first [31].

$$2\Delta\omega_r p_{14}(e_{\alpha s}\hat{\varphi}_{\beta r} - e_{\beta s}\hat{\varphi}_{\alpha r}) - 2\left(\frac{\Delta\omega_r}{\rho}\right)\frac{d\hat{\omega}_r}{dt} = 0. \quad (17)$$

Thus,

$$\hat{\omega}_r = \rho p_{14} \int (e_{\alpha s}\hat{\varphi}_{\beta r} - e_{\beta s}\hat{\varphi}_{\alpha r}) dt. \quad (18)$$

To improve the accuracy of the estimation, many researchers have proposed a PI-type adaptation mechanism. The following expression of the estimated speed is obtained:

$$\hat{\omega}_r = \left(K_p + \frac{K_i}{s}\right)(e_{\alpha s}\hat{\varphi}_{\beta r} - e_{\beta s}\hat{\varphi}_{\alpha r}), \quad (19)$$

where K_p and K_i are positive constants which can be adjusted.

4. Motor Commands

4.1. Active Disturbance Rejection Controller. The IFOC for a FL-HBCI fed induction motor sensorless system can be affected by different internal (variation of resistance) and external perturbations (load torque, variation of speed). For that, ADRC is used as a robust control approach. Its principle is that all failures, disturbances, and uncertainties are handled in real-time as “total perturbation” through being calculated and compensated [25, 32]. It can estimate the whole perturbation as an extended state of the system by the introduction of the extended state observer (ESO).

For our case, the system is of the first order. In general, the canonical form of the first-order system is [33]

$$y = f(y, \varepsilon, t) + b_0 u, \quad (20)$$

where u is the input variable; y is the output variable, and b_0 is the constant. ε represents the whole of external and internal disturbances

Equation (20) can be written following in the state-space form as:

$$\begin{cases} \dot{x} = Ax + b_0 Bu + Eh, \\ y = Cx, \end{cases} \quad (21)$$

with

$$\begin{aligned} A &= \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \\ E &= \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \\ B &= \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \\ C &= \begin{pmatrix} 1 \\ 0 \end{pmatrix}^T, \\ x &= \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \\ h &= \dot{f}. \end{aligned} \quad (22)$$

The ESO can be presented by the following equation:

$$\begin{cases} \dot{x}_1 = b_0 u + x_2, \\ \dot{x}_2 = \dot{f}, \\ y = x_1. \end{cases} \quad (23)$$

The linear ESO can be expressed as

$$\begin{cases} \dot{z} = Az + b_0 Bu + L(y - \hat{y}), \\ \hat{y} = Cz, \end{cases} \quad (24)$$

where L is the observer gain vector:

$$L = \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} 2\omega_0 \\ \omega_0^2 \end{pmatrix}, \quad (25)$$

with ω_0 being the bandwidth of the observer. It is determined by the pole placement, to ensure the fast and good output, with a minimum of noise [34].

An ADRC well-tuned can compensate the total of disturbance. The control law is defined by

$$u = \frac{u_0 - z_2}{b_0}. \quad (26)$$

with z_2 being a correct estimation of “ f ” and z_1 a correct estimation of “ y ”.

Equation (20) becomes

$$\begin{cases} \dot{y} = u_0 + (f - z_2) \approx u_0, \\ u_0 = k_p(g - z_1), \end{cases} \quad (27)$$

where g is the reference input signal.

Figure 2 shows the structure of an ADRC. It consists of three blocks.

In our case, equations (2)–(4) can be rearranged to be written in the canonical form of ADRC. It can be described by the following equations:

FIGURE 1: Structure of conventional FL cascaded H-bridge.

$$\begin{cases} \frac{di_{ds}}{dt} = f_d(i_{ds}, \varepsilon, t) + b_0 u_d(t), \\ \frac{di_{qs}}{dt} = f_q(i_{qs}, \varepsilon, t) + b_0 u_q(t), \\ \frac{d\Omega}{dt} = f_\Omega(\Omega, \varepsilon, t) + b_{0\omega} u(t), \end{cases} \quad (28)$$

with

$$\begin{aligned} b_0 &= \frac{1}{L_s \sigma}, \\ b_{0\omega} &= \frac{1}{J}, \\ u_d &= V_{ds}, \\ u_q &= V_{qs}, \\ u &= C_{elm}, \end{aligned} \quad (29)$$

where b_0 and $b_{0\omega}$ are the known part in the controller tuning, when selecting the adequate response time. The parameters of the ADRC can be found easily.

Figure 3 shows the ADRC-IFOC scheme of the FLI-HBC feeding induction motor sensorless.

4.2. PI Controller. Figure 4 shows the PI controllers applied on the FLI-HBC fed induction motor sensorless.

The parameters of the PI controllers have been adjusted by a method based on a criterion giving a better compromise between the response time and the overshoot.

5. Simulation Results and Discussion

The proposed ADRC-IFOC of FL-HCBI fed induction motor sensorless scheme with three ADRC controllers (speed and currents controllers) is presented in Figure 4. The outputs of the ADRC flow and torque controllers are uncoupled, to ensure the decoupling of the IFOC approach. Therefore, three references are generated for the SPWM modulator. The induction motor receives input signals from the FL-HCB inverter. The speed is estimated using the Luenberger estimator.

The simulation was conducted on the platform MATLAB-Simulink. The numerical parameters of the induction motor are provided in Table 1.

To evaluate the performances of the suggested ADRC control for FL-HCBI fed IM sensorless, different conditions are applied. Therefore, the reference speed value is maintained to $A7B7 = [90 \ 130 \ 50] \text{ rad/s}$ at $\{0 \ 2 \ 6\} \text{ s}$. In addition, the load disturbance torque is applied at $\{3 \ 5 \ 7.5 \ 8.5\} \text{ s}$ with the values $[5 \ -5 \ 6 \ -6] \text{ N.m}$. The suggested system is compared to the control for FL-HCBI fed IM sensorless based on the PI.

Initially, the simulation result of the output voltage for FL-HCBI on ADR-IFOC sensorless is obtained and shown in Figures 5 and 6.

5.1. Speed Variation and Load Torque Variation. Figure 7 shows the output of rotor speed of both systems; they successfully operated. From the figure, it can be seen that the response speed with ADRC follows more quickly the reference speed, despite the variation of torque, compared to the output speed with PI.

It is clear in Figure 8 that the torque performance of the system with ADRC is better than that with the use of the classical PI controller. Indeed, when the speed reference steps up from 90 rad/s to 130 rad/s at 2 s and at 6 s, we notice

that the response torque with ADRC rejects rapidly the perturbation.

Figure 9 portrays the result of direct current for both of the systems. It is observed that ripples are more reduced with ADRC than with PI.

Figures 10 and 11 indicate the result of stator phase current for PI and ADRC, respectively, applied to the suggested system.

Moreover, the error of speed achieved both with the classic PI and with ADRC is shown in Figure 12. It is made

TABLE 1: Three-phase IM parameters.

Parameter	Symbol	Value
Principal machine inductance	L_s	0,3973 H
Secnder machine inductance	L_r	0,3558 H
Stator resistance	R_r	5.4
Mutual inductance	L_m	0,39 H
Number of pole pairs	P	2
Inertia moment	J	0,02 kg.m ²
Viscous friction coefficient	f_v	0,0025 N.m.s/rad
Power	P	1 kw

FIGURE 5: Voltage waveform for FL-HBCI on ADR-IFOC (zoom of V_{a0} ; V_{b0} ; V_{c0}). FIGURE 6: Voltage waveform for FL-HBCI on ADR-IFOC (zoom of V_{ab}).

FIGURE 7: The result of rotor speed of the FL-HCBI fed induction motor sensorless under torque variation.

FIGURE 8: The result of torque for PI and ADRC used in the sensorless control IM fed by FL-HCBI.

clear that the biggest tracking error of speed occurs for the system with PI.

From the simulation results, it can be seen that the FL-HCBI IM obtains satisfactory performance in sensorless control with a minimum of ripples.

From the comparison, both systems give satisfactory results; the torque ripples have minimized with the use of FL-HCBI.

The system with PI requires more time to settle down when there is a variation of reference speed or application of disturbance. Moreover, some ripples are visible more than the system with ADRC. However, the system with ADRC

handles the disruption better than PI. It can return to the steady state rapidly after sudden changes (such as the application of load torque). The ADRC improves system resistance against disturbances; therefore, it increases the ruggedness of the suggested system.

5.2. Resistance Variation and Load Torque Variation. For induction motor control system, the resistances of IM may suddenly vary, due to temperature variation with the operation time of IM. For that, the rotor and stator resistances parameters are selected, to evaluate the robustness of both systems under parameters variation and in worst cases.

FIGURE 9: The result of direct current for PI and ADRC used in the sensorless control IM fed by FL-HBCI.

FIGURE 10: The result of stator phase current for PI used in the sensorless control IM fed by FL-HBCI.

Firstly, the value of the rotor resistance is increased by 100% from its nominal resistance.

Figure 13 shows the simulation results of the ADRC and PI systems, with the same response time, under rotor resistance variation.

Figure 14 shows the simulation results of the ADRC and PI systems, with the same response time, under stator

resistance variation. Its value is increased by 50% from its nominal stator value.

Figures 13 and 14 indicate that when the motor reaches 90 rad/s. At 0.6 s, the system with ADRC follows smoothly the reference speed despite the variation of resistance. Nevertheless, the system with PI has an overshoot. When the load torque increases suddenly from

FIGURE 11: The result of stator phase current for ADRC used in the sensorless control IM fed by FL-HBCI.

FIGURE 12: The result of error speed for PI and ADRC used in the sensorless control IM fed by FL-HBCI.

FIGURE 13: The result of rotor speed for PI and ADRC under rotor resistance.

FIGURE 14: The result of rotor speed for PI and ADRC under stator resistance.

0 N to 5 N, the speed output has a smaller fluctuation with ADRC. Meanwhile, the rotor speed with PI takes more time to return to its steady state.

It can be noted from the simulation results that the proposed method with ADRC is more robust than the system with PI because it can compensate the disturbance caused by the variation of rotor and stator resistances.

6. Conclusions

In this paper, to improve the performance of the control, a vector control scheme sensorless was proposed for FL-HBCI feeding IM based on ADRC.

To compensate the external (the load torque) and internal (resistances variation) disturbances, the application of

three ADRC to the system in sensorless vector control system has been proposed, instead of the PI controllers. The ADRC contains the ESO that can estimate and compensate the load disturbances and the sudden change.

The LO has been used to estimate the rotor speed. Furthermore, the FL-HBCI has been incorporated into the system to achieve the output with a minimum of losses.

From the simulation results, the proposed system makes the system more robust. Rapid response time and accurate output are achieved using the suggested control system.

The results also prove a high performance of the proposed solution and confirm that the system with ADRC is better and stiffer than the classical PI control under the different scenarios and disturbance conditions.

As a perspective of this work, we intend to compare the performance of the proposed method to the main existing methods.

Data Availability

No data used to support the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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