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Nonlinear Sensorless Control of Doubly Fed Induction Machines in Electric Vehicles

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Nonlinear Sensorless Control of Doubly Fed Induction Machines in Electric Vehicles

T. Roubache, F. Berrabah, and S. Chaouch

Abstract—**This article addresses a sensorless control design based on an extended Kalman Filter (EKF) to estimate the state of a doubly-fed induction motor (DFIM) model. This kind of motor is operating as an actuator in electric vehicle (EV) with optimal performance. Thus, a nonlinear model is adopted to simultaneously allow a simpler observability system analysis and a more effective state estimation. The obtained results clearly show both better performance of this suggested control, and the structure of power provided to the machine.**

***Keywords*—Doubly-fed induction motor (DFIM), Extended Kalman Filter (EKF), Second order sliding mode control (SOSMC), Electric vehicle (EV).**

NOMENCLATURE

$V_{s\alpha\beta}$, $V_{r\alpha\beta}$	Stator/Rotor voltage (V)
R_s, R_r	Stator/Rotor resistance (Ω)
$i_{s\alpha\beta}$, $i_{r\alpha\beta}$	Stator/Rotor current (A)
$\varphi_{s\alpha\beta}$, $\varphi_{r\alpha\beta}$	Stator/Rotor flux (wb)
ω	Rotor angular speed (rad/s).
L_m, L_r, L_s	Mutual, Rotor, and Stator inductance (H).
J, k_f	Inertia moment ($kg.m^2$) and viscous friction ($N.m.s/rad$)
T_e, T_l	Electromagnetic/Load torque ($N.m$)

I. Introduction

The double-fed induction machines (DFIMs) are frequently employed in applications where mechanical energy needs to be converted to electrical energy, such as hydraulic and wind systems [1, 2], as well as in applications that require motor mode operating, such as railway traction, naval propulsion, and electric/hybrid vehicles [3]. In addition, the DFIM is the most used thanks to its great performance and energy quality [4]-[6]. However, the coupling of the flux and electromagnetic torque is inevitable because of the nonlinearity of these sorts of machines. Thus, a control approach that permits the decoupling of these variables is required.

To achieve a decoupling between the control variables with speed control variables of the motor, different nonlinear control techniques have been proposed to address this problem. Among these strategies, the second order sliding mode control (SOSMC) is used, applying a super twisting algorithm (ST) because it offers a suitable alternative for attaining higher performance in terms of speed, accuracy and stability.

The conventional sliding mode controls delivers good robustness against potential system perturbations and uncertainties, while achieving convergence properties in a limited time [7]. However, the main issue linked to SMC is the occurrence of chattering phenomenon, which results in the control of the use of law in a discontinuous signum function [8]. By addressing discontinuous sign function in a derivative of some sliding mode variables, the SOSMC with ST has smaller chattering and has more precision than the SMC [9].

Sensorless control systems using doubly fed induction motors as actuators need estimating the rotor speed and the rotor flux components, which cannot be measured directly.

So, this article focuses the following suggestions:

- A sensorless control using an EKF observer.

- Design of SMC based on ST algorithm strategy for DFIM in EVs application.

However, a lot of obstacles occur with installing the sensor, additional expenses…etc., while using the sensors [10].

The purpose of this study is to investigate the usage of doubly-fed induction machines in electric propulsion.

The structure of this paper is as follows: Section 2, is interested in the modeling of the motor investigated in reference frame (α,β). The synthesis of the SMC applied to DFIM is shown in Section 3. In Section 4, the machine's sensorless control is designed. In section 5, simulation and test results are included. At the end, a conclusion and some remarks are added.

II. Mathematical Modeling

A. DFIM Model

The machine model in reference (α,β) is expressed as follows:

$$\begin{cases} V_{s\alpha} = R_s i_{s\alpha} \dot{\varphi}_{s\alpha} \\ V_{s\beta} = R_s i_{s\beta} \dot{\varphi}_{s\beta} \\ V_{r\alpha} = R_r i_{r\alpha} \dot{\varphi}_{r\alpha} + \omega \varphi_{r\beta} \\ V_{r\beta} = R_r i_{r\beta} \dot{\varphi}_{r\beta} - \omega \varphi_{r\alpha} \end{cases} \tag{1}$$

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$$\begin{cases} i_{s\alpha} = b_1\varphi_{s\alpha} - b_1\frac{L_m}{L_r}\varphi_{r\alpha} \\ i_{s\beta} = b_1\varphi_{s\beta} - b_1\frac{L_m}{L_r}\varphi_{r\beta} \\ i_{r\alpha} = b_2\varphi_{r\alpha} - b_2\frac{L_m}{L_r}\varphi_{s\alpha} \\ i_{r\beta} = b_2\varphi_{r\beta} - b_2\frac{L_m}{L_r}\varphi_{s\beta} \end{cases} \quad (2)$$

where: $\sigma = 1 - \frac{L_m}{L_s L_r}, b_1 = \frac{1}{\sigma L_s}, b_2 = \frac{1}{\sigma L_r}$

The DFIM's magnetic equations in reference (α,β) are expressed as follows:

$$\begin{cases} \varphi_{s\alpha} = L_s i_{s\alpha} + L_m i_{r\alpha} \\ \varphi_{s\beta} = L_s i_{s\beta} + L_m i_{r\beta} \\ \varphi_{r\alpha} = L_r i_{r\alpha} + L_m i_{s\alpha} \\ \varphi_{r\beta} = L_r i_{r\beta} + L_m i_{s\beta} \end{cases} \quad (3)$$

The DFIM's mechanical equations are as follows:

$$\begin{cases} J\dot{w} = T_e - T_r - k_f\omega \\ T_e = p\left(i_{s\alpha}\varphi_{s\beta} - i_{s\beta}\varphi_{s\alpha}\right) \end{cases} \quad (4)$$

Thus, this system is controlled via a variety of nonlinear sensorless strategies, such as: Flux oriented control (FOC), Direct torque control (DTC), Backstepping control,…etc. Moreover, SMC strategy can be used. It has good performance because of the insensitivity to the nonlinearity of the system and to external disturbance. The major problem of this control is the chattering phenomenon. Consequently, many researchers developed a new technique based on a controller using ST sliding mode [11]-[13]. To address this issue, a control strategy by using a SOSMC is designed based on ST algorithm.

B. EV Dynamic Model

The dynamic equation of vehicle can be described as follows [14]:

$$\begin{cases} J_t\frac{dV_v}{dt} = \sum F_{tr}\, R \\ F_{tr} = F_a + F_r + F_p \end{cases} \quad (5)$$

with:

$$\begin{cases} F_a = 0.5\rho S_f C_d (V_v \pm V_w) \\ F_r = M_v g C_r \\ F_p = M_v g sin(\alpha) \end{cases} \quad (6)$$

where: J_t, R, ρ, S_f, M_v, C_d, C_r, V_v, V_w are total inertia, wheel radius, air density, frontal area and mass of the vehicle, aerodynamic and rolling coefficient, vehicle and wind speed, respectively.

III. Nonlinear Sensorless Control

A. SMC

The conventional SMC is a variable structure control with the ability to commute between two values and change structure in accordance with a very specialized switching logic [15]. The system can transit between structures at any time via switching logic and structure selection. Moreover, selecting the switching surface *S(x)* number is the first step in the control design process. Generally, the number of sliding surfaces is chosen such that it equals the control vector's dimension.

The sliding surface's general form is primarily addressed as follows:

$$S(x) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(x) \quad (7)$$

with *e(x)* is the tracking error vector, λ is a positive coefficient, and *n* is the system order.

First, consider the following Lyapunov function to determine the attractiveness condition:

$$V(s) = \frac{1}{2}S^2 \quad (8)$$

The time derivative of equation (8) must be negative as a necessary and sufficient condition [16]:

$$\dot{S}S < 0 \quad (9)$$

Second, the equivalent control is obtained thanks to the following conditions of invariance of the surface: $\dot{S} = S = 0$ [17].

Thus, the global control is given by addition of the nonlinear component u_n and an equivalent control u_e providing a convergence and a sliding regime as follows:

$$\begin{cases} u = u_n + u_e \\ u_n = -\gamma sign(S) \end{cases} \quad (10)$$

where: γ is a positive constant.

Finally, to exceed the issue of chattering in this kind of control, SOSMC combined with ST algorithm has been introduced. It has been designed for the control of systems with respect to the sliding surface [18]. Thus, the ST consists of two parts: a continuous part u_1 and a discontinuous part u_2 [19], [20].

$$u = u_1 + u_2 \quad (11)$$

with:

$$u_1 = \begin{cases} -\lambda|S_0|^\Gamma sign(S) & if\ |u| > S_0 \\ -\lambda|S|^\Gamma sign(S) & if\ |u| \le S_0 \end{cases} \quad (12)$$

$$u_2 = \begin{cases} -u & if\ |u| > U_M \\ -\gamma sign(S) & if\ |u| \le U_M \end{cases} \quad (13)$$

When applying the SOSMC on the DFIM, the control surface of the rotor speed and rotor flux can be expressed as follows:

$$\begin{cases} S_1 = k_1\left(w_{ref} - w_r\right) + \left(\dot{w}_{ref} - \dot{w}_r\right) \\ S_2 = k_2\left(\Phi_{ref} - \Phi_r\right) + \left(\dot{\Phi}_{ref} - \dot{\Phi}_r\right) \end{cases} \quad (14)$$

where: k_1 and k_2 are positive gains

The corresponding derivative of (14) is given by:

$$\begin{cases}\dot{S}_1 = k_1\left(\dot{w}_{ref} - \dot{w}_r\right) + \left(\ddot{w}_{ref} - \ddot{w}_r\right) \\ = k_1\left(\dot{w}_{ref} - \frac{1}{J}\left(-\frac{pL_m}{L_s}\left(i_{r\beta}\varphi_{s\alpha}\right) - k_f w_r - T_l\right)\right) + F_1 \\ \dot{S}_2 = k_2\left(\dot{\Phi}_{ref} - \dot{\Phi}_r\right) + \left(\ddot{\Phi}_{ref} - \ddot{\Phi}_r\right) \\ = k_2\left(\dot{\Phi}_{ref} - V_{r\alpha} + \frac{L_m}{T_r} i_{s\alpha} - \frac{1}{T_r}\varphi_{r\alpha}\right) + F_2\end{cases} \quad (15)$$

with:

$$\begin{cases}F_1 = \left(\ddot{w}_{ref} - \ddot{w}_r\right) \\ F_2 = \left(\ddot{\Phi}_{ref} - \ddot{\Phi}_r\right)\end{cases} \quad (16)$$

The EKF equations are given as follows [22], [23]:

$$\begin{cases}P(k+1\,|k) = F(k)P(k)F(k)^T + Q \\ K(k+1) = P(k+1\,|k)C^T\left[CP(k+1\,|k)C^T + R\right]^{-1}) \\ \hat{X}(k+1) = g\left[\hat{X}(k), u(k)\right] + K(k)\left[Y(k) - C\hat{X}(k)\right]\end{cases} \quad (18)$$

where $\hat{X}$ is the full estimation of the DFIM's state, $P(k)$ is the estimation error covariance matrix, $K(k)$ is the EKF gain matrix, C and $F(k)$ are expressed as follows:

$$\begin{cases}C = \frac{\partial}{\partial X}\{c_d(X(k),k)\} \\ F(k) = \frac{\partial}{\partial X}\{g[X(k),u(k),k]\}\end{cases} \quad (19)$$

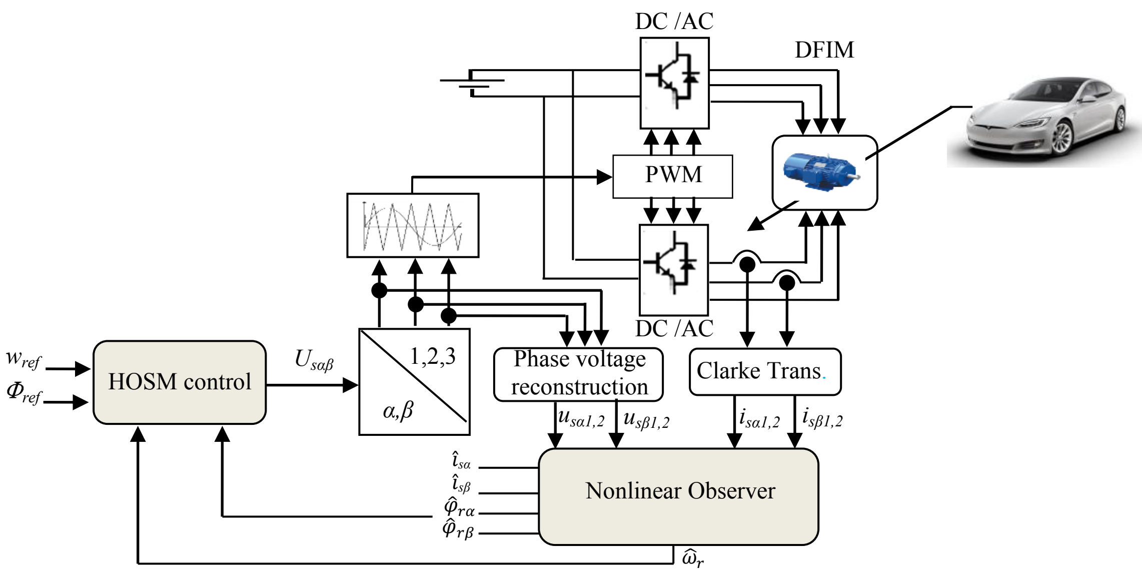

Figure 1. Schematic of double fed induction motor sensorless control using an EKF observer

B. Extended Kalman Filter

The EKF observer is a stochastic filter for nonlinear dynamical systems. The EKF will be employed to estimate the full-state and the DFIM's speed model using current measurements.

To obtain an estimate of the real valued state X of the nonlinear model (2)–(4), an EKF has to be considered [21]:

$$\begin{cases}X(k+1) = g[X(k),u(k),k] + b_{rs}(k) \\ Y(k+1) = c_d X(k) + b_{rm}(k)\end{cases} \quad (17)$$

where c_d, $b_{rs}(k)$, and $b_{rm}(k)$ are the output matrix, the process and measurement noise at time k, respectively. The covariance matrix of noise vector, which is shown below:

$$Q = cov(w) = E\{ww^T\};\ R = cov(v) = E\{vv^T\}$$

where: R, Q, and $E\{\ \}$ are the measurement covariance matrices, the process, and the mathematical expectation, respectively [21].

IV. Simulation Results

The suggested nonlinear sensorless control has used an EKF and nominal parameters of DFIM (see Appendix). The machine is powered through two PWM voltage inverters, one at the rotor and the other at the stator. These converters are both supplied by a continuous source. HOSMC is realized, which uses ST algorithm. In this case, the speed and flux loops are closed by using the proposed EKF providing a full estimation of the DFIM state. Figure (1) illustrates the schematic diagram of the drive system.

A. Robustness analysis

In this section, a robustness study of the proposed control is carried out, to evaluate its ability to produce correct state estimation through variation parameters. The DFIM has been operated with a rotor flux of 1 Wb. The simulation results are presented for the following two tests: The first test is carried out by analyzing the behavior of the EKF when the rotor and the stator resistance are increased up to 50% of its nominal value at t = 3s.

To evaluate the robustness of the suggested sensorless control, the second test is important to check the influence of the low speed variation. The tracking performance of this test is shown in Fig. 3.

Fig. 2a shows the rotor speed estimation and its zoom. According to the obtained results, we can observe that the influence of these parameters' variations is small, which shows a good robustness of the suggested sensorless control.

Figs. 2b, c and d show that the rotor flux component, the electromagnetic torque ripple using, and the EV velocity, respectively.

From the results obtained, we notice that with this suggested control, the electromagnetic torque ripple is smaller and both parts of the figure show average amplitude of the rotor flux around the reference, and the EV velocity follow its profile. Consequently, highest robustness can be achieved by ST algorithm.

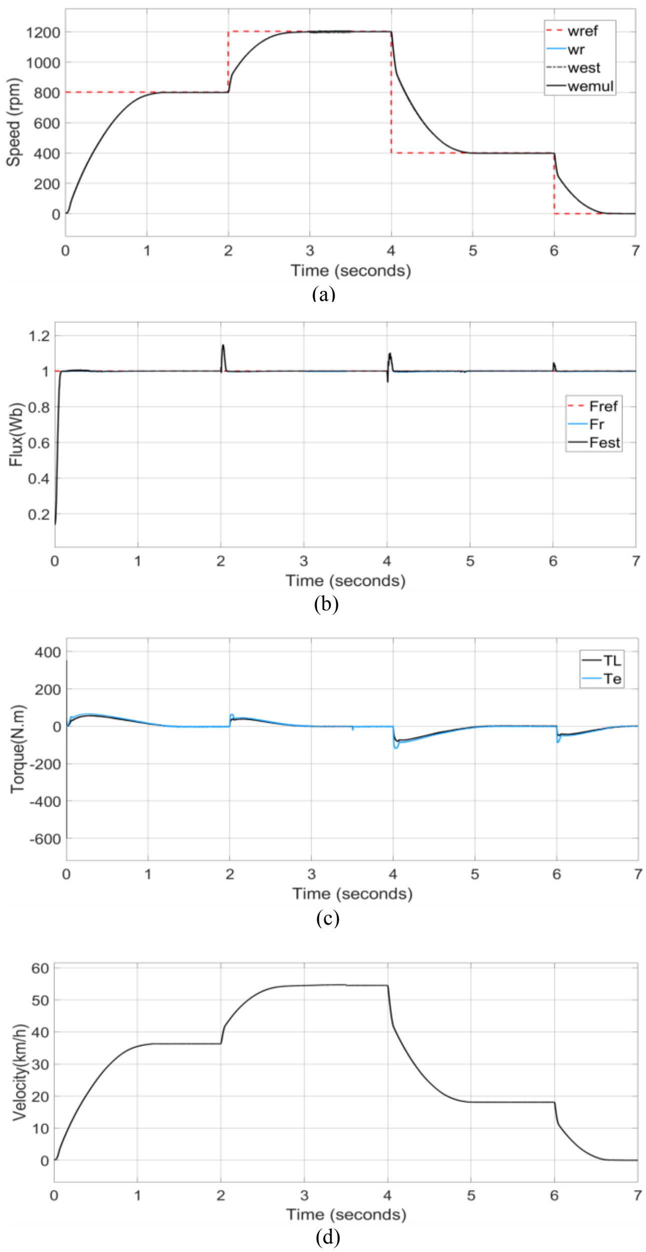

Figure 2 . Test 1 tracking performance: a) rotor speed, b) rotor flux, c) electromagnetic torque, d) EV velocity

As a result, these results have less chattering and respond appropriately to the suggested variation.

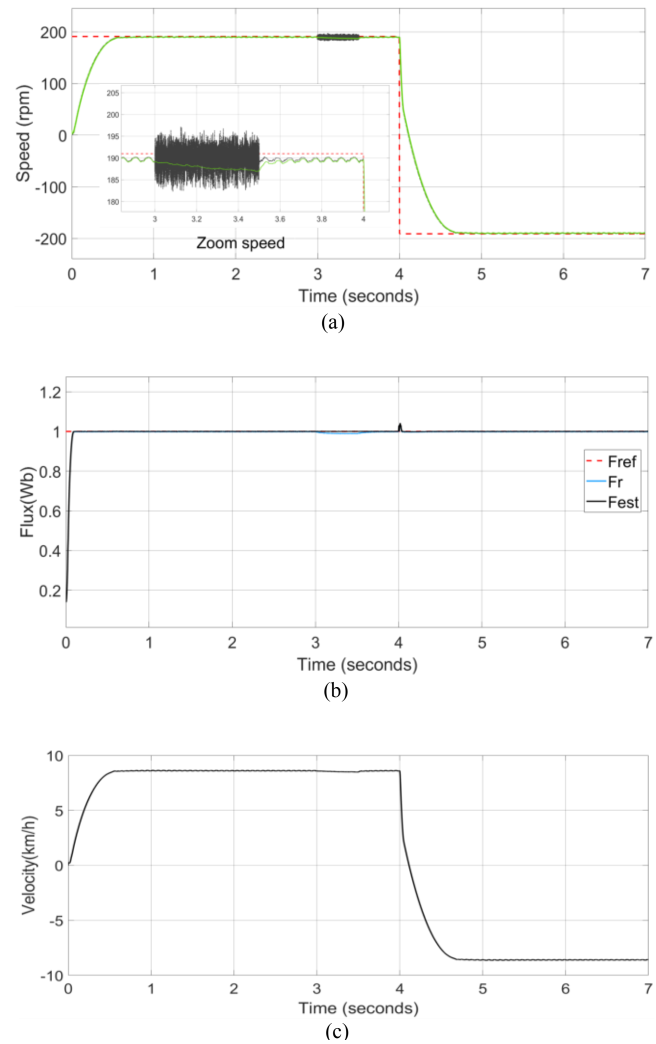

Figure 3. Test 2 rotor speed variation: a) rotor speed, b) rotor flux, c) EV velocity

From Figs. 3a, b and c, we have registered a better response for rotor speed, rotor flux, and EV velocity when minor errors for the speed and rotor flux are obtained. Moreover, these results confirm that the control scheme, even at low speed variation, has good robustness and tracking performance.

V. Conclusion

This paper has presented a nonlinear sensorless control of double-fed induction motor based on SOSMC combined with ST algorithm in electric vehicle application.

The simulation tests have confirmed the performance of the suggested scenarios for steady state responses of speed and flux, even at variable speed profile, and with the introduction of the disturbances.

It is obvious, from the results obtained, that the suggested sensorless control gives better performance.

APPENDIX

TABLE I. DOUBLY FED INDUCTION MOTOR PARAMETERS

Nominal parameters	Used values
Power	1 kw
Rotor Resistance	3.805 Ω
Stator Resistance	4.85 Ω
Rotor/Stator Inductance	0.274 H
Mutual Inductance	0.258 H
Rotor Inertia	0.031 kg.m^2

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