PSYCHOLOGY AND EDUCATION (2024) 61(5): 773-789
ISSN: 1553-6939

Design of Induction motor drive system using alternative controllers for performance evaluation in electric vehicle applications

Djaghdali Lakhdar [1]
Department of electrical Engineering, University of Msila, Algeria
The Author's E-mail: djaghdali.lakhdar@univ-msila.dz [1]

Received: 01/2024 **Published: 05/2024**

Abstract:

We present in this paper a comparative study between two control strategy of Induction Motor that propels an electrical vehicle: Direct Torque Control (DTC-SVM), and Predictive Direct Torque Control (MPDTC). The first algorithm based on load angle control is developed. The use of simple equations to obtain the control algorithm makes it easy to understand and implement. Fixed switching frequency and low torque ripple are obtained using space vector modulation. This control strategy overcomes the most important drawbacks of classic DTC. We also present in the second algorithm, the Predictive Direct Torque Control based on the linearization input-output of the induction machine. The technique of the linearization is used for to give a model linearized and decoupled from the machine for anticipating the future behavior of the output. The comparison is based on several criteria including: static and dynamic performance, structure and implementation complexity, decoupling, torque and current ripple.

Keywords-Electric drives, Induction motor, Electrical vehicle, Direct torque control, Predictive direct torque control, Space vector modulation.

1. INTRODUCTION

In the last decade, the increasing restrictions imposed on the exhaust emissions from internal combustion engines and the traffic limitations in the urban areas have given a strong impulse toward the development of electrical propulsion systems for automotive applications. The major goal of electrical and hybrid vehicles is the reduction of global emissions, which in turn leads to a decrease of fuel resources exploitation.

The major components of an electric vehicle system are motor, controller, power source; charger and drive train. The majority of electric vehicles (EV) developed so far are based on dc machines, induction machines or permanent magnet machines. The disadvantages of dc machines forced the EV developers to look into various types of ac machines.

The power density of permanent magnet machines together with the high cost of permanent magnets makes these machines less attractive for EV applications. The maintenance-free and low-cost induction machines became a good attractive alternative to many developers. However, high-speed operation of induction machines is only possible with a penalty in size and weight. Three-phase squirrel cage-rotor induction motors are best suited to electric vehicle drive applications thanks to its well-known advantage of simple construction, reliability, ruggedness, and low cost.

The constantly increasing need for better industrial drives (fastest dynamic response, parameter robustness, algorithm simplicity, among others) has encouraged researchers to develop new control strategies to comply with these requirements. New alternatives to both linear and nonlinear methods have been proposed using predictive algorithms to achieve high-bandwidth control loops [1]. The main difficulty in the asynchronous machine control resides in the fact that complex coupling exists between the field and the torque, the direct torque control assures decoupling between these variables.

We present in this paper a comparative study between two control strategy of electrical machines. The first section a control algorithm DTC-SVM, based on PI controllers. The algorithm retains the basic idea of the technique DTC [2] [3]. For this, the technique of orientation of the stator flux is used. Thus, the control voltages can be generated by PI and imposed by SVM technique [4]. In addition the estimate of the torque and flux is based on the model of the machine voltage [5]. This control structure has the advantages of vector control and direct torque control and helps overcome the problems of conventional DTC [6]. PI and vector modulation technique is used to obtain a fixed switching frequency [7] and less torque pulsations and flux [8]. The input of the motor controller is the reference speed, which is directly applied by conductor from the pedal of the vehicle.

The second section, the Predictive Direct Torque Control based on the linearization input-output of electrical machine, this control is a technique of advanced control automation [9]. It aims to control complex industrial systems [10]. The principle of this technique is to use a dynamic model of the process inside the controller in real time to anticipate the future behavior of the process [11]. It is to be optimized, based on inputs/outputs of a system, predicting the future behavior of the system under consideration. The prediction is made from an internal model of the system on a finite interval of time called the prediction horizon [12]. The solution of the optimization problem is a control vector; the first input of the optimal sequence is injected into the system. The problem is solved again on the following interval using the data system updates [13][14].This control strategy has shown its efficiency, flexibility and success in industrial applications, even for systems with low sampling period [15].

This paper is organized on fifth sections. The control methods by DTC-SVM and MPDTC will be discussed in section two and three. In the fourth we present the comparison of simulation results. Finally, a general conclusion summaries this work. The simulation results are obtained by using Matlab/Simulink.

2. DTC-SVM control based on the control of the load angle:

In the proposed method, the control objective is to select the exact stator voltage vector (V_S) that changes Φ_S to meet the load angle reference, and so the desired torque while keeping flux amplitude constant. A space vector modulation algorithm is used to apply the required stator voltage vector.

The block diagram of the control structure is shown in (Fig. 1). This strategy uses a single torque controller, which operates on the angle between the stator flux and the rotor flux (Fig.2), known as the load angle **δ**, and a simple estimation block flux rotor [16]. We see in this method there is not a rotation transformation in the block header of the SVM, and we have a single PI controller; making the simple strategy applied to control. The input of the motor controller is the reference speed, which is directly applied by conductor from the pedal of the vehicle.

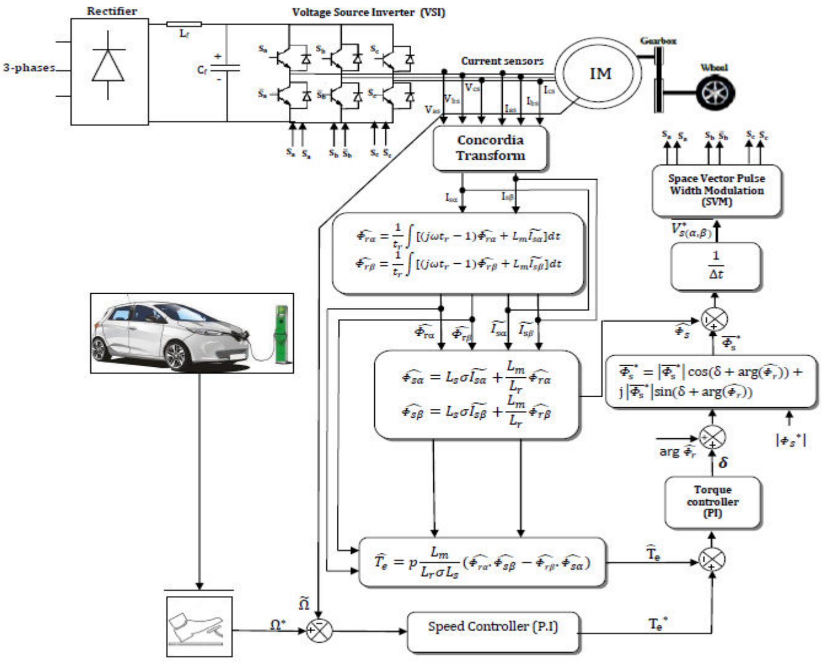


Fig. 1 Schema Block of DTC-SVM control based on the control of load angle.

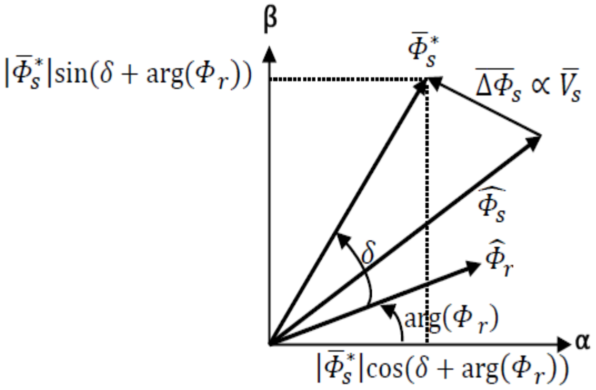


Fig. 2 Load angle between the reference stator flux and rotor flux

A. Estimation of the rotor flux:

To implement the estimation of the rotor flux we remember the model of the following machine data:

$$\begin{cases} \overline{V_s} = R_s.\overline{I_s} + \frac{d\overline{\Phi_s}}{dt} \\ \overline{V_r} = 0 = R_r.\overline{I_r} + \frac{d\overline{\Phi_r}}{dt} - j\omega\overline{\Phi_r} \\ \overline{\Phi_s} = L_s.\overline{I_s} + L_m.\overline{I_r} \\ \overline{\Phi_r} = L_r.\overline{I_r} + L_m.\overline{I_s} \end{cases} \tag{1}$$

By according: Equation (2) of system (1), we can write:

$$\frac{d\overline{\Phi_r}}{dt} = -R_r.\overline{I_r} + j\omega\overline{\Phi_r} \tag{2}$$

And equation (4) of system (1):

$$\overline{I_r} = \frac{1}{L_r}\overline{\Phi_r} - \frac{L_m}{L_r}.\overline{I_s} \tag{3}$$

By injecting (3) in (2) found:

$$\frac{d\overline{\Phi_r}}{dt} = -\frac{R_r}{L_r}.\overline{\Phi_r} + \frac{L_m R_r}{L_r}\overline{I_s} + j\omega\overline{\Phi_r} \tag{4}$$

And as $\mathrm{t_r} = \frac{\mathrm{L_r}}{\mathrm{R_r}}$ we can write:

$$\frac{d\overline{\Phi_r}}{dt} = -\frac{1}{t_r}.\overline{\Phi_r} + \frac{L_m}{t_r}\overline{I_s} + j\omega\overline{\Phi_r} \tag{5}$$

$$= \frac{1}{t_r}[(j\omega t_r - 1)\overline{\Phi_r} + L_m\overline{I_s}]$$

$$d\widehat{\Phi_r} = \frac{1}{t_r}\left[(j\omega t_r - 1)\widehat{\Phi_r} + L_m\widetilde{I_s}\right]dt$$

$$\widehat{\Phi_r} = \frac{1}{t_r}\int\left[(j\omega t_r - 1)\widehat{\Phi_r} + L_m\widetilde{I_s}\right]dt \tag{6}$$

B. Estimation of the stator flux:

By injecting the relation (3) in equation (3) of system (1) found:

$$\overline{\Phi_s} = L_s.\overline{I_s} + L_m.\left(\frac{1}{L_r}\overline{\Phi_r} - \frac{L_m}{L_r}.\overline{I_s}\right)$$

$$\widehat{\Phi_s} = L_s\sigma\widetilde{I_s} + \frac{L_m}{L_r}\widehat{\Phi_r} \text{ With: } \sigma = 1 - \frac{L_m^2}{L_r L_s} \tag{7}$$

C. Estimation of the electromagnetic torque:

The torque estimation formula is given by:

$$\widehat{C_e} = p\frac{L_m}{L_r\sigma L_s}\left(\widehat{\Phi_r}\otimes\widehat{\Phi_s}\right)$$

$$= p\frac{L_m}{L_r\sigma L_s}\left(\widehat{\Phi_{r\alpha}}.\widehat{\Phi_{s\beta}} - \widehat{\Phi_{r\beta}}.\widehat{\Phi_{s\alpha}}\right) \tag{8}$$

The bloc of estimate the flux and the torque from the measured stator currents and the speed of rotation are shown in Fig. 3:

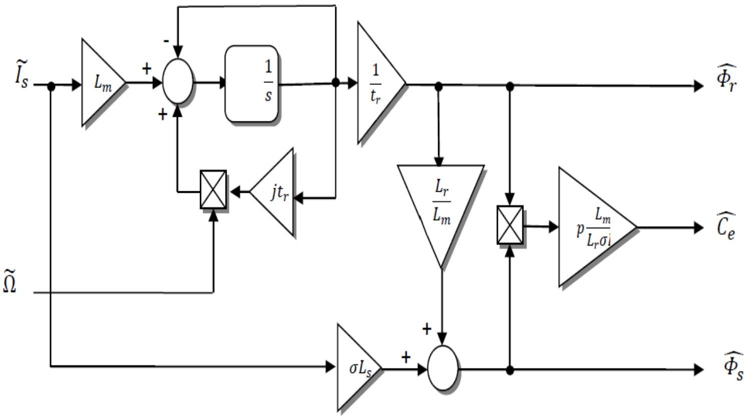


Fig. 3 Block diagram of flux and torque estimators

The block calculator of stator flux reference is given by:

$$\overline{\Phi_s^*} = |\overline{\Phi_s^*}| \cos\left(\delta + \arg\left(\widehat{\Phi_r}\right)\right) + j|\overline{\Phi_s^*}| sin\left(\delta + \arg\left(\widehat{\Phi_r}\right)\right) \qquad (9)$$

3. Predictive Direct Torque Control (MPDTC)

The Predictive control is a technique of advanced control automation. It aims to control complex industrial systems [9]. The principle of this technique is to use a dynamic model of the process inside the controller in real time to anticipate the future behavior of the process [11].

A. General Strategy of Predictive Control

The basic principle of predictive control is taken into account, at the current time, the future behavior, through explicit use of a numerical model of the system in order to predict the output in the future, on a finite horizon [17][18].One of the advantages of predictive methods lies in the fact that for a pre-calculated set on a horizon, it is possible to exploit the information of predefined trajectories located in the future, given that the aim is to match the output of system with this set on a finite horizon.

B. Formulation of The Model

All algorithms predictive control differs from each other by the model used to represent the process and the cost function to be minimized [13]. The process model can take different representations (transfer function by state variables, impulse response...), we will give for our formulation, the technique of the linearization input-output of the induction machine [19], in order to give a linearized model; module of the stator flux and the torque are decoupled. The interest of such approach is to linearize the nonlinear model of the machine and to obtain a homogeneous behavior whatever the point of operation.We recall the system of the equations of the induction machine in the reference (α,β) which is given by:

$$\begin{cases} \frac{dI_{s\alpha}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) I_{s\alpha} - \omega_r I_{s\beta} + \frac{R_r}{\sigma L_r L_S}\phi_{s\alpha} + \frac{\omega_r}{\sigma L_S}\phi_{s\beta} + \frac{1}{\sigma L_S}V_{s\alpha} \\ \frac{dI_{s\beta}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) I_{s\beta} + \omega_r I_{s\alpha} + \frac{R_r}{\sigma L_r L_S}\phi_{s\beta} - \frac{\omega_r}{\sigma L_S}\phi_{s\alpha} + \frac{1}{\sigma L_S}V_{s\beta} \\ \frac{d\phi_{s\alpha}}{dt} = V_{s\alpha} - R_s I_{s\alpha} \\ \frac{d\phi_{s\beta}}{dt} = V_{s\beta} - R_s I_{s\beta} \end{cases} \qquad (10)$$

The generated torque can be expressed in terms of currents stator and stator flux as follows:

$$T_e = p\left(\phi_{s\alpha} I_{s\beta} - \phi_{s\beta} I_{s\alpha}\right) \tag{11}$$

The system of equations east receives in the form suggested for the application of the linearization within the meaning of the input-output as follows:

$$\begin{cases} \dot{x} = f(x) + \mathrm{g}_1(x) V_{s\alpha} + \mathrm{g}_2(x) V_{s\beta} \\ \qquad\qquad y = \mathrm{h(x)} \end{cases} \tag{12}$$

With:

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \end{bmatrix} = \begin{bmatrix} -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) I_{s\alpha} - \omega_r I_{s\beta} + \frac{R_r}{\sigma L_r L_S}\phi_{s\alpha} + \frac{\omega_r}{\sigma L_S}\phi_{s\beta} \\ -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) I_{s\beta} + \omega_r I_{s\alpha} + \frac{R_r}{\sigma L_r L_S}\phi_{s\beta} - \frac{\omega_r}{\sigma L_S}\phi_{s\alpha} \\ -R_s I_{s\alpha} \\ -R_s I_{s\beta} \end{bmatrix}$$

Where the vector of states $\boldsymbol{x}$ and the command $\boldsymbol{u}$ are:

$$x = \left[I_{s\alpha}, I_{s\beta}, \phi_{s\alpha}, \phi_{s\beta}\right]^t, \; u = [V_{s\alpha}, V_{s\beta}]^t$$

$$\mathrm{g}_1(x) = \left[\frac{1}{\sigma L_s}, 0, \; 1, \; 0\right]^t, \quad \mathrm{g}_2(x) = \left[\,0, \; \frac{1}{\sigma L_s}, \; 0, \; 1\right]^t$$

a. Control Flux-Torque :

Our concern is to minimize the pulsations at the level of the torque and the flux of the induction machine. For that, we chose the torque and the module of stator flux like variables to be controlled; thus the vector of output is given by the equation according to:

$$y = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} T_e \\ |\emptyset_s|^2 \end{bmatrix} = \begin{bmatrix} p\left(\phi_{s\alpha} I_{s\beta} - \phi_{s\beta} I_{s\alpha}\right) \\ \phi_{s\alpha}^2 + \phi_{s\beta}^2 \end{bmatrix} \tag{13}$$

b. Linearization Input-Output:

The method of the linearization input-output is developed starting from the theories of the differential geometry [20]. It consists in using the derivative of degrees to express the model of the machine in relation input-output. To obtain the non-linear law of control, let us derive as much from time than it is necessary in order to reveal the entry u. The derivatives of the two outputs are given by:

$$\begin{aligned} \dot{y}_1 &= L_f h_1(x) + L_{g1} h_1(x) V_{s\alpha} + L_{g2} h_1(x) V_{s\beta} \\ &= \textstyle\sum_{i=1}^{4} \frac{\partial h_1}{\partial x_i} f_i(x) + \sum_{i=1}^{4} \frac{\partial h_1}{\partial x_i} g_1(x) V_{s\alpha} + \sum_{i=1}^{4} \frac{\partial h_1}{\partial x_i} \mathrm{g}_2(x) V_{s\beta} \end{aligned} \tag{14}$$

With:

$$\boldsymbol{L_f h_1} = -p\phi_{s\beta}\left[-\left(\frac{R_s}{\sigma L_s}+\frac{R_r}{\sigma L_r}\right)I_{s\alpha} - \omega_r I_{s\beta} + +\frac{R_r}{\sigma L_r L_S}\phi_{s\alpha} + \frac{\omega_r}{\sigma L_S}\phi_{s\beta}\right] + p\phi_{s\alpha}\left[-\left(\frac{R_s}{\sigma L_s}+\frac{R_r}{\sigma L_r}\right)I_{s\beta} + \omega_r I_{s\alpha} + \frac{R_r}{\sigma L_r L_S}\phi_{s\beta} - \frac{\omega_r}{\sigma L_S}\phi_{s\alpha}\right]$$

$$\boldsymbol{L_{g1} h_1} = p(I_{s\beta} - \frac{1}{\sigma L_s}\phi_{s\beta}) \qquad (15)$$

$$\boldsymbol{L_{g2} h_1} = p(\frac{1}{\sigma L_s}\phi_{s\alpha} - I_{s\alpha})$$

$$\dot{y_2} = L_f h_2(x) + L_{g1} h_2(x) V_{s\alpha} + L_{g2} h_2(x) V_{s\beta}$$

$$= \sum_{i=1}^{4}\frac{\partial h_2}{\partial x_i} f_i(x) + \sum_{i=1}^{4}\frac{\partial h_2}{\partial x_i} g_1(x) V_{s\alpha} + \sum_{i=1}^{4}\frac{\partial h_2}{\partial x_i} \mathrm{g}_2(x) V_{s\beta} \qquad (16)$$

With:

$$\boldsymbol{L_f h_2} = -2R_s(\phi_{s\alpha} I_{s\alpha} - \phi_{s\beta} I_{s\beta})$$

$$\boldsymbol{L_{g1} h_2} = 2\phi_{s\alpha} \qquad (17)$$

$$\boldsymbol{L_{g2} h_2} = 2\phi_{s\beta}$$

c. *Linearization of the System:*

The matrix defining the relation between the inputs of the system and its derived outputs is given by the expression:

$$\begin{bmatrix}\dot{y}_1\\ \dot{y}_2\end{bmatrix} = A(x) + D(x)\begin{bmatrix}V_{S\alpha}\\ V_{S\beta}\end{bmatrix} \qquad (18)$$

With: $A(x) = \begin{bmatrix}L_f h_1\\ L_f h_2\end{bmatrix}$; $D(x) = \begin{bmatrix}L_{g1}h_1 & L_{g2}h_1\\ L_{g1}h_2 & L_{g2}h_2\end{bmatrix} = \begin{bmatrix}p(I_{s\beta} - \frac{1}{\sigma L_s}\phi_{s\beta}) & p(\frac{1}{\sigma L_s}\phi_{s\alpha} - I_{s\alpha})\\ 2\phi_{s\alpha} & 2\phi_{s\beta}\end{bmatrix}$

$D(x)$: Matrix of decoupling.

$$\mathrm{Det}[D(x)] = p\left(I_{s\beta} - \frac{1}{\sigma L_s}\phi_{s\beta}\right).2\phi_{s\beta} - p\left(\frac{1}{\sigma L_s}\phi_{s\alpha} - I_{s\alpha}\right).2\phi_{s\alpha} \qquad (19)$$

After simplification, we get:

$$\mathrm{Det}[D(x)] = 2p\left[\frac{-1}{\sigma L_s}\left({\phi_{s\beta}}^2 + {\phi_{s\alpha}}^2\right) + I_{s\beta}\phi_{s\beta} + I_{s\alpha}\phi_{s\alpha}\right] \neq \mathbf{0} \qquad (20)$$

The determinant (Det$[D(x)]$) of the matrix D$(x)$is different from zero; therefore D$(x)$is an invertible matrix.

$$D^{-1}(x) = \frac{1}{2p\left[\frac{-1}{\sigma L_s}({\phi_{s\beta}}^2 + {\phi_{s\alpha}}^2) + I_{s\beta}\phi_{s\beta} + I_{s\alpha}\phi_{s\alpha}\right]}\begin{bmatrix}2\phi_{s\beta} & -p(\frac{1}{\sigma L_s}\phi_{s\alpha} - I_{s\alpha})\\ -2\phi_{s\alpha} & p(I_{s\beta} - \frac{1}{\sigma L_s}\phi_{s\beta})\end{bmatrix} \qquad (21)$$

The linearization following input-output which is introduced for the system illustrated by (12) is given by:

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = D^{-1}(x)\left[-A(x) + \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}\right] \tag{22}$$

$V = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$: represent the new vector of input.

The application of the law linearizing (22) on the system (18) led to two linear and decoupled mono variable system:

$$\begin{cases} V_1 = \dot{h_1}(x) \\ V_2 = \dot{h_2}(x) \end{cases} \tag{23}$$

To ensure perfect regulation and track the desired signals of the flux and torque toward their reference, V_1 and V_2 are chosen as follows:

$$\begin{cases} \mathrm{V}_1 = |\dot{\emptyset}_\mathrm{s}|^2_\mathrm{ref} + \mathrm{k}_1\left(|\emptyset_\mathrm{s}|^2_\mathrm{ref} - |\emptyset_\mathrm{s}|^2\right) \\ \quad \mathrm{V}_2 = \dot{\mathrm{T}}_\mathrm{e\,ref} + \mathrm{k}_2(\mathrm{T}_\mathrm{e\,ref} - \mathrm{T}_\mathrm{e}) \end{cases} \tag{24}$$

Here, the subscript 'ref' denotes the reference value and (k_1, k_2) are constant design parameters to be determined in order to make the decoupled system in (18) stable. The behavior of the linearized model is imposed by the pole placement method. The coefficients selected, such as $s + k_1$ and $s + k_2$, are the Hurwitz polynomials [17].[18].

4. Criterion of Optimization

We must find the future control sequence to apply on the system to reach the desired set point by following the reference trajectory. To do this, we just minimize a cost function which differs according to the methods, but generally this function contains the squared errors between the reference trajectory and the predictions of the prediction horizon and the variation of the control [17]. This cost function is given as follows:

$$J = \sum_{j=N_1}^{N_2}[w(t+j) - \hat{y}(t+j)]^2 + \lambda \sum_{j=1}^{N_u} \Delta u(t+ j-1)^2 \tag{25}$$

With:

$w(t + j)$: Set point applied at time $(t + j)$.

$\hat{y}(t+j)$: Output predicted time $(t + j)$.

$\Delta u(t + j-1)$: Increment of control at the moment $(t + j-1)$.

N_1: Minimum prediction horizon on the output.

N_2: Maximum prediction horizon on the output, with $N_2 \geq N_1$.

N_u : Horizon prediction on the order.

λ: Weighting factor on the order.

T_s: The period of sampling.

The model is linearized and decoupled from the induction machine, so that it is established inside the predictive control, which is shown by (Fig. 4).

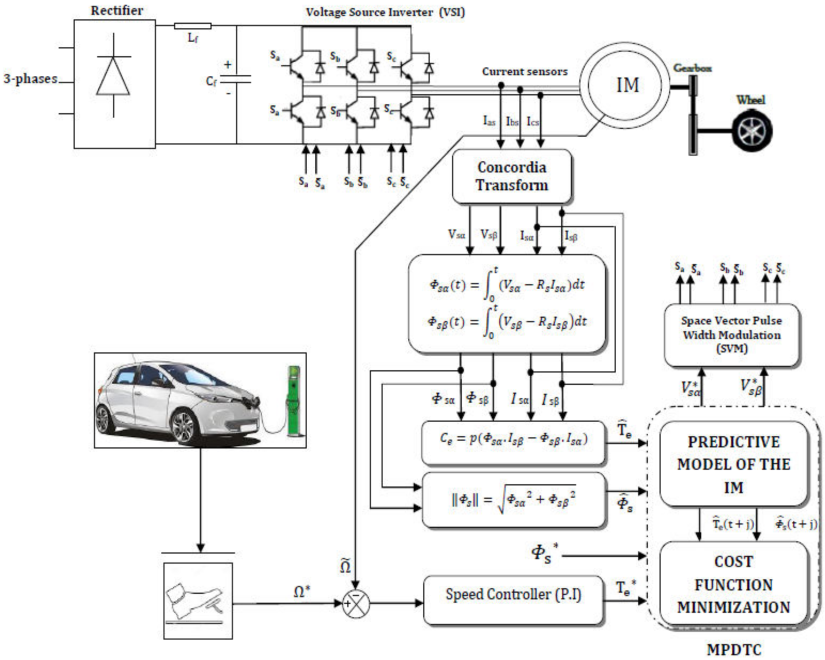


Fig. 4 Schema block of the predictive direct torque control

5. Results of Simulations

a. *Electromagnetic torque*

It is found that the predictive direct torque control has a high dynamic performance of the electromagnetic torque acting very quickly by following the instructions load introduced. The latter has are mark able decrease in the amplitude of the oscillations from the DTC-SVM.

b. *The speed of rotation*

It is found that the speed reaches its reference Ω_{ref} =100 rd/s without overshoot and releases disturbance due to load instructions applied to various for mentioned moments are eliminated. Predictive direct torque control this release very fast perturbation that the DTC-SVM.

c. The stator flux

The module of the stator flux is quickly established at its reference value 1.11 Weber in both control techniques. The approach to predictive DTC has a visible reduction in oscillation amplitude and the modulus of the flux with respect to the DTC-SVM. The dynamic component of the stator flux is not affected by the application of the load command.

d. The stator current

Predictive control has a large inrush current at startup with swings and revenue Is the steady state after 0.28s. This current has a sinusoidal shape compared to the DTC-SVM.

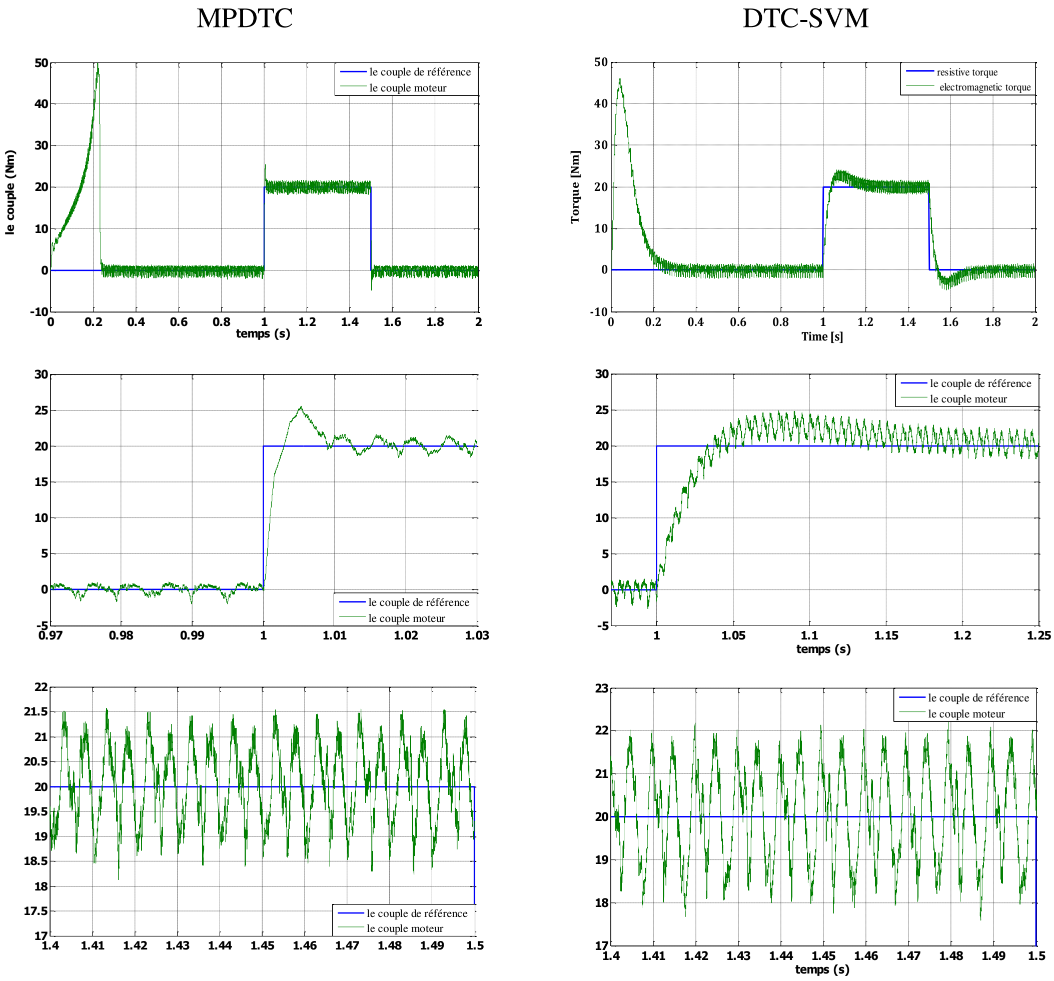


Fig. 5 Comparison of the electromagnetic torque

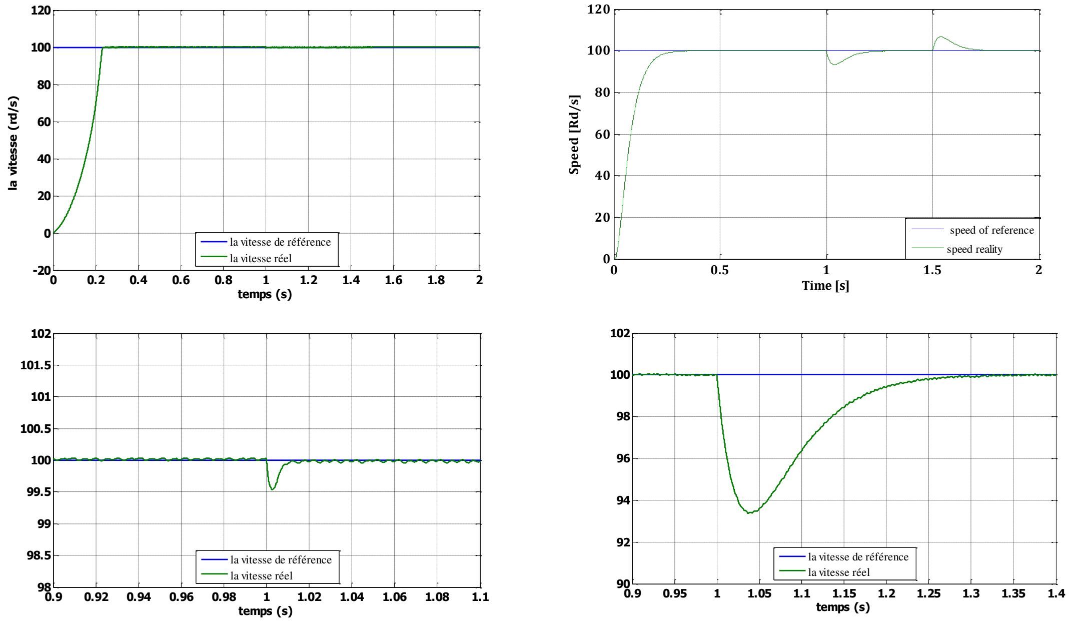


Fig.6 Comparison The speed of rotation

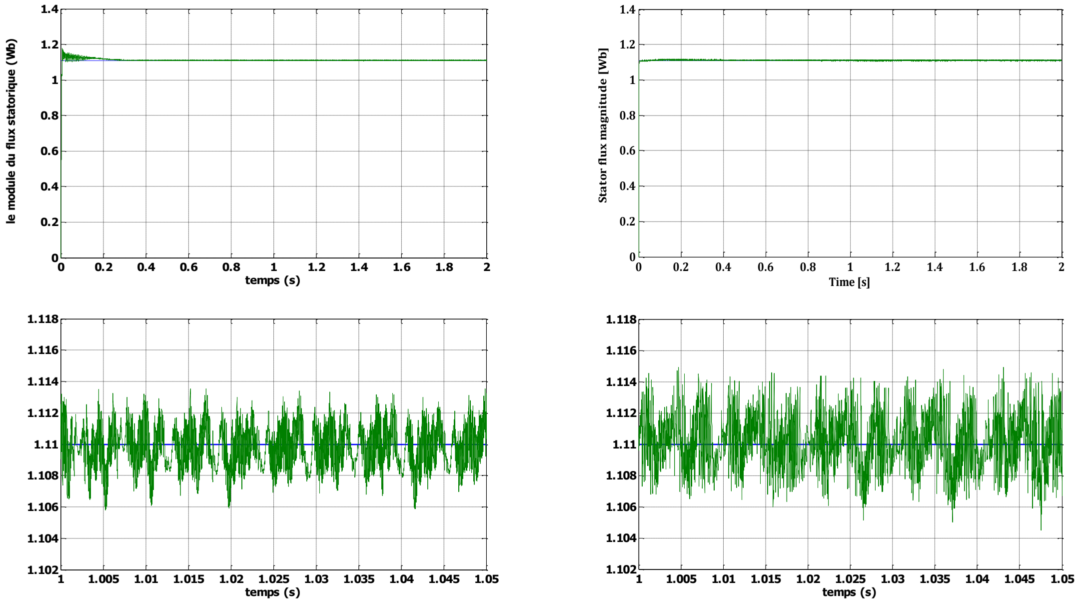
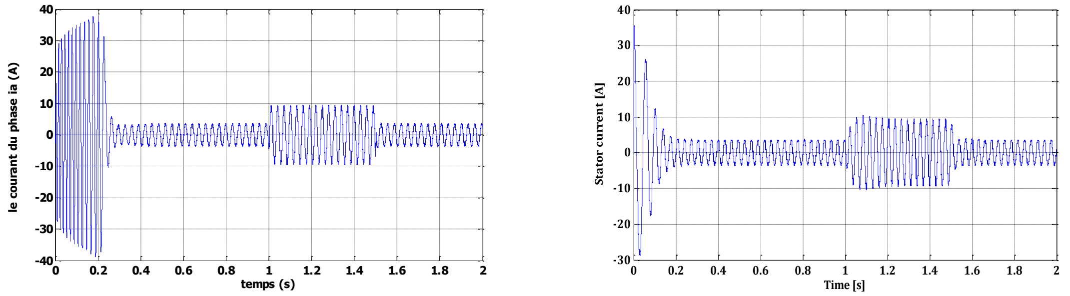


Fig.7 Comparison of The stator flux



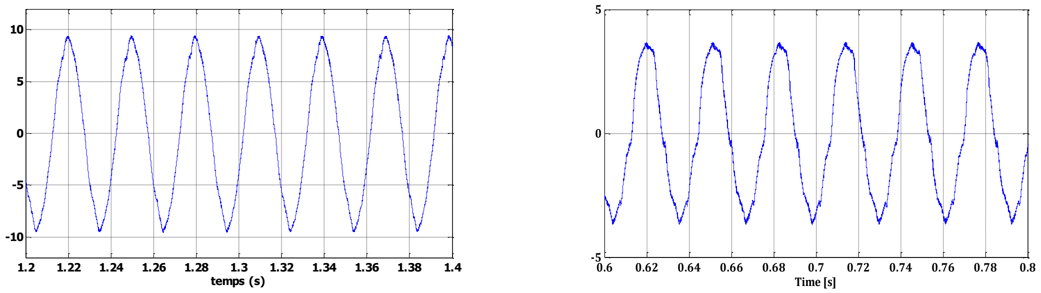


Fig.8 Comparison of The stator current

The table below summarizes the results of the comparative study treated previously. In fact, from the table, one can choose the approach to be used according to the needed objectives, the desired performances and the available means.

Control Approach	**DTC-SVM**	**MPDTC**
Commutation frequency	fixed	fixed
Electromagnetic torque ripples	high	low
Stator flux ripples	high	low
Switching losses	high	low
rejection of disturbance	Bad	good
Algorithm complexity	low	high

6. Conclusion

This paper has presented two switching techniques for DTC of an induction motor drive that propels an electric vehicle, the principle and a several characteristics of Direct Torque Control and Predictive Direct Torque Controls chemes for Induction Motor drive are studied by simulation in order to determinate the main advantages and drawbacks of each control and to make a comparison between them.

The simulation results show that MPDTC control provides high dynamic performance in torque and stator flux module, as well as disturbance rejection at speed. The stator current is sinusoidal. (less harmonics), comparing with the DTC-SVM.

Note, however, that the toughness can be improved by increasing the weighting factor by acting on the adjustment parameters of the predictive controller. These parameters have a decisive influence on the system behavior. But it is not always easy to find optimal values for these parameters.

CHARACTERISTICS OF THE MACHINE USED FOR SIMULATION:

parameter	*symbol*	*Value*
Number of pole pairs	p	2
Power	P_u	3 KW
Line voltage	U_n	380V
Line current	I_n	6.3A
Nominal frequency	f	50Hz
Mechanical rotor speed	N_n	1430 tr/mn
Electromagnetic torque	T_e	20Nm
Stator Resistance	R_s	3.36Ω
Rotor Resistance	R_r	1.09Ω
Stator cyclicinductance	L_s	0.256H
Mutual cyclic Inductance	L_m	0.236H
Rotor cyclic inductance	L_r	0.256H
Rotor inertia	j	$4{,}5.10^{-2}$Kg. m
Viscosity coefficient	f	$6{,}32.10^{-4}$N. m.sec.

RÉFÉRENCES

[1] H. Miranda, P.Cortés, Juan I. Yuz, and J.Rodriguez.“*Predictive Torque Control of Induction Machines Based on State-Space Models*”. IEEE Trans. Ind. Electron, VOL. 56, NO. 6, JUNE 2009.

[2] I. Takahashi, Y. Ohmori. “ *High-Performance Direct Torque Control of an Motor* ”. IEEE Trans. on Industrial Applications, 25(2):257–264, March/April 1989.

[3] M. Depenbrock. “ *Direct Self-Control (DSC) of Inverter-Fed Induction Machine* ”. IEEE Trans. on Power Electronics, 3(4):420–429, October 1988.

[4] D. Casadei, G. Serra, A. Tani.“ *Implementation of a Direct Torque Control Algorithm for Induction Motors Based on Discrete Space Vector Modulation* ”. IEEE Trans. on Power Electronics, 15(4):769–777, July 2000.

[5] L. Tang, L. Zhong, A. F. Rahman, Y. Hu, “*An investigation of a modified direct torque control strategy for flux and torque ripple reduction for induction machine drive system with fixed switching frequency*”, IEEE-IAS Industry Applications Conf., 2002.

[6] Y.S. Lai, J.H. Chen. “*A New Approach to Direct Torque Control of Induction Motor Drives for Constant Inverter Switching Frequency and Torque Ripple Reduction*”. IEEE Trans. on Energy Conversion,16(3):220–227, September 2001.

[7] D. Casadei, G. Serra, A. Tani, L. Zarri, F. Profumo. “*Performance Analysis of a Speed-Sensorless Induction Motor Drive Based on a Constant-Switching-Frequency DTC Scheme*”. IEEE Trans. on Industry Applications, 39(2):476–484,

Marhc/April 2003.

[8] L. Tang, M.F. Rahman. “*A New Direct Torque Control Strategy for Flux and Torque Ripple Reduction for Induction Motors Drive by Using Space Vector Modulation*”. IEEE PESC 32nd International Conference, pages 1440–1445, 2001

[9] D. Krušelj D. Sumina “Modified predictive torque control method of induction machines for torque ripple reduction”
Journal for Control, Measurement, Electronics, Computing and Communications,Vol 60, 2019 - Issue 2, Pages 227-238.

[10] A. Ammar, A. Bourek, A. Benakcha “Nonlinear SVM-DTC for induction motor drive using input-output feedback linearization and high order sliding mode control” ISA TransactionsVol 67, March 2017, Pages 428-442.

[11] M. Mamdouh; M. Ali Abido “Efficient Predictive Torque Control for Induction Motor Drive” IEEE Transactions on Industrial Electronics Vol 66, Issue: 9, September 2019, Page(s): 6757 – 6767.

[12] T. J. Meijer ; S. A. N. Nouwens “Finite-Horizon Minimal Realizations for Model Predictive Control of Large-Scale Systems” 2022 IEEE 61st Conference on Decision and Control (CDC)

[13] V. Prasad Muddineni; A. Kumar Bonala “Grey Relational Analysis based objective Function Optimization for Predictive Torque Control of Induction Machine” 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020).

[14] H. Miranda; P. Cortes “Predictive Torque Control of Induction Machines Based on State-Space Models” IEEE Transactions on Industrial Electronics Vol: 56, Issue: 6, June 2009 Page(s): 1916 - 1924

[15] Tobias Englert, Knut Graichen “Nonlinear model predictive torque control and setpoint computation of induction machines for high performance application”Control Engineering PracticeVol 99, June 2020, 104415

[16]. José Rodriguez, Jorge Pontt, César Silva, Samir Kouro and Hernan Miranda "A Novel Direct Torque Control Scheme for Induction Machines With Space VectorModulation". 35th Annuel IEEE Power Electronics Specialists Conference, Aachen, Germany, 2004.

[17] Wei Xu; JianqiaoZou “Improved Model Predictive Current Control Strategy-Based Rotor Flux for Linear Induction Machines” IEEE Transactions on Applied Superconductivity Vol: 26, Issue: 7, October 2016.

[18] M. Norambuena; J. Rodriguez “A Very Simple Strategy for High-Quality Performance of AC Machines Using Model Predictive Control” IEEE Transactions on Power Electronics Vol: 34, Issue: 1, January 2019 Page(s): 794 – 800.

[19]L. djaghdali, S. belkacem, F.naceri, “ Reducing of torque and flux ripples in DTC of IM based on predictive control”*Journal of Electrical Engineering* Year: 2016.

[20] M. Fatima; H. Assia “The Non Linear Multivariable Control of an Asynchronous Machine” 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM).