Finite States Predictive Torque and Flux control fed by an Indirect Converter with and without energy storage

Zakaria Lammouchi, Kamel Barra
Department of Electrical Engineering
Larbi Ben M'hidi university, Oum El Bouaghi, 04000. Algeria
Prof_lammouchiz@yahoo.fr, barakamel@yahoo.fr

Abstract— **The paper presents an improved predictive direct control of a variable speed. The method is based on finite states space model of the converter. The proposed control method selects the optimal switching state of (Indirect Converter with and without energy storage for rectified and inverted) that minimizes the error between orthogonal torque, fluxs, and the reactive power components predictions to their computed values for all different voltage vectors. The optimal voltage vector that minimizes a cost function has been applied to the output of the power converter. The proposed predictive control strategy uses only one sample time prediction and it is very intuitive for implementation, and provides best performances.**

Index Terms— indirect matrix converter (IMC), States Model Predictive Control (FS-MPC), cost function, AC/DC/AC converter, dc-link voltage.

I. Introduction

Indirect AC – DC – AC converter is the most common approach for AC – AC power conversion. The converter topology consists of a rectifier at supply side and an inverter at the load side. The distinctive feature of this converter topology is the need of energy storage element in the intermediate DC-link: a capacitor for a VSI. Due to low cost and control simplicity, the indirect AC-DC-AC converter has been extensively used an industrial applications [1].

The main disadvantage of the indirect AC-DC-AC converter topology is the need for a large energy storage element in the DC-link. Compared to other electronic components, electrolytic capacitors have a shorter lifetime. As a result, the overall lifetime of the converter is reduced, leading to the increased maintenance cost. Also, the energy storage elements are bulky and unreliable at extreme temperatures, causing this converter topology to be inappropriate for some applications, the converter will become more susceptible to grid disturbances [2]. In order to eliminate the need for DC-link energy storage, the indirect converter without energy storage technology has gained significant research interest. The matrix converter is able to generate sinusoidal supply currents and adjustable input power factor irrespective of the load. Most importantly, the removal of the DC-link energy storage element enables the matrix converter topology to have a more compact design, which is an advantage in applications such as aerospace.

Recently; Finite-States Model Predictive Control (FS-MPC) appears as a complete and accurate approach to control power converters due to its fast dynamic response, no need for linear controllers in inner loops [3], no need for modulator (as in PWM or SVM modulation), completely different approach compared to PWM and SVM modulations, extremely simple, very good performance and can be implemented with standard commercial microprocessors. The method is based on the fact that a finite number of possible switching states can be generated by power converter (7 states for a two-level three- phase inverter) and that the model of the system can be used to predict the behaviour of the variables for each switching state. For the selection of the appropriate switching state to be applied to the system a quality function must be defined. The cost function is then evaluated for the predicted values on each sampling interval and the optimal switching state that minimizes the quality function is selected to apply during the next sampling interval [4][5][6].

A predictive FS-MPC is presented in this work for the control of the AC/DC/AC converter. In the proposed control strategy, the finite possible switching states of the AC/DC/AC are considered, the effect of each one on the load current and input power is evaluated, and the switching state that minimizes a quality function is selected and applied during the next sampling period. The quality function evaluates the error between orthogonal torque and fluxs components predictions to their computed values for all different voltage vectors for the inverter, and the reactive power error for the rectifier. A similar strategy has been presented at the indirect matrix converter (without energy storage), to control in an easy, an intuitive and a new manner, the torque and flux variables of an induction machine fed by the converter while ensuring a unitary power factor at the input system of the converter.

II. Indirect converter AC/DC/AC with storage energy

This paper presents a new control scheme for a regenerative AC/DC/AC converter using model based Predictive control. The control strategy minimizes quality functions, which represent the desired behavior of the converter. The AC/DC/AC converter model shown in Fig. 1 is considered. For a simpler analysis, the converter can be separated mainly in rectifier and inverter sides.
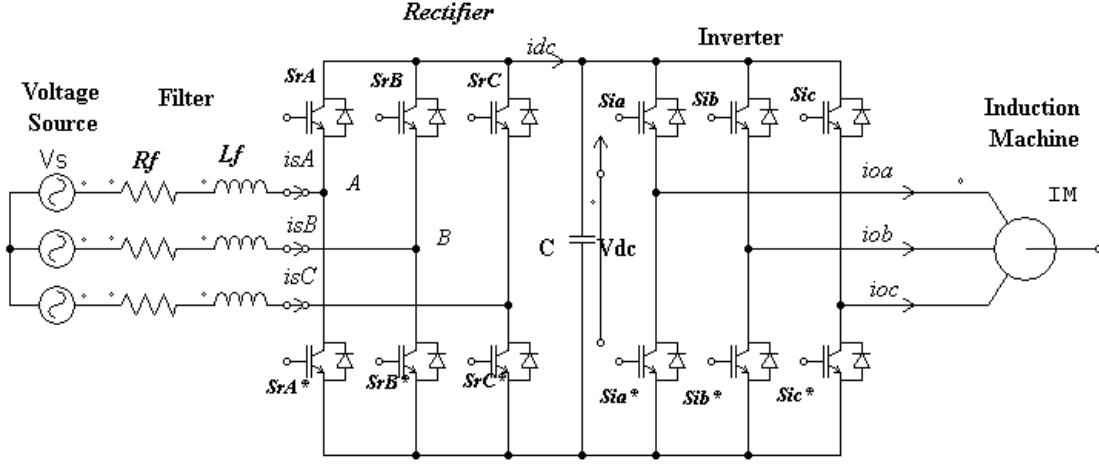

Fig. 1: Indirect Converter (AC/DC/AC) power topology
With energy storage

II.1. Rectifier side

The rectifier is a fully controlled power switch bridge connected to the three-phase supply voltages v_s using the filter inductances L_f and resistances R_f.
The input current dynamics can be described in the stationary frame $(\alpha\beta)$ by the vector equation:

$$L_f \frac{di_s}{dt} = V_s - V_{rec} - R_f i_s \tag{1}$$

where i_s is the input current vector, V_s is the supply line voltage and $V_{rec} = S_r * V_{dc}$ is the voltage generated by the converter. The input current vector is related to the phase currents by the equation:

$$i_s = \frac{2}{3}\left(i_{sA} + a i_{sB} + a^2 i_{sC}\right) \tag{2}$$

where $a = e^{\frac{2\pi}{3}}$. The voltages V_s and V_{rec} are defined in a similar way, and S_r is the switching state vector for the rectifier and is defined as:

$$S_r = \frac{2}{3}\left(S_{rA} + a S_{rB} + a^2 S_{rC}\right) \tag{3}$$

where S_{rA}, S_{rB} and S_{rC} are the switching states of each rectifier leg, as shown in Fig. 1, and take the value of 0 if S_x is off, or 1 if S_x is on.

II.2.. Inverter side

For a two level voltage source inverter feeding a symmetrical three-phase induction motor given in fig.2, each leg is composed of two by-directional switches (S_{i1}, S_{i2} $i=a,b,c$) where a,b,c the three phases. The switching states S determined by gating signals are given in a vectorial form as follows:

$$S_i = \frac{2}{3}\left(S_{ia} + a S_{ib} + a^2 S_{ic}\right) \tag{4}$$

The voltage V_{inv} is linked to the inverter switching state S_i : $V_{inv} = S_i V_{dc}$
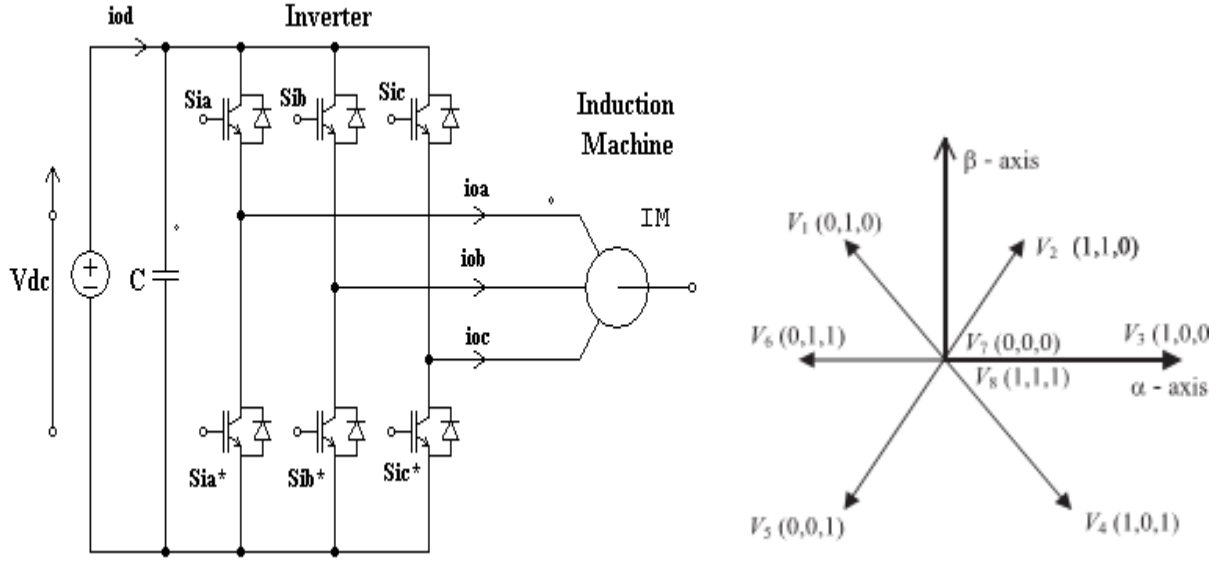
Fig.2: Two level source inverter with different voltage vectors

II.3. Minimization of cost function

II.3.1. CONTROL OF THE INVERTER SIDE

The control of the inverter side is similar to the scheme presented in [7]. The effect of each possible voltage vector, generated by the inverter, on the behavior of the load current is evaluated using a quality function G_i. The voltage vector that minimizes this function is selected and applied during the next sampling period [5] as can be shown in fig.3-4 . The quality function to be minimized for the inverter the tracking error between reference and predicted measured torque, stator flux , which is expressed in orthogonal coordinates as

$$G_i = \alpha \frac{\left(T_e^*(k+1)-T_e(k+1)\right)^2}{T_n^2} + \beta \frac{\left(\psi_s^*(k+1)-\psi_s(k+1)\right)^2}{\psi_n^2} \tag{5}$$

where T_n and ψ_n are the nominal torque and nominal stator flux values, and α,β,λ are the weight coefficients which denotes the priority in the control.
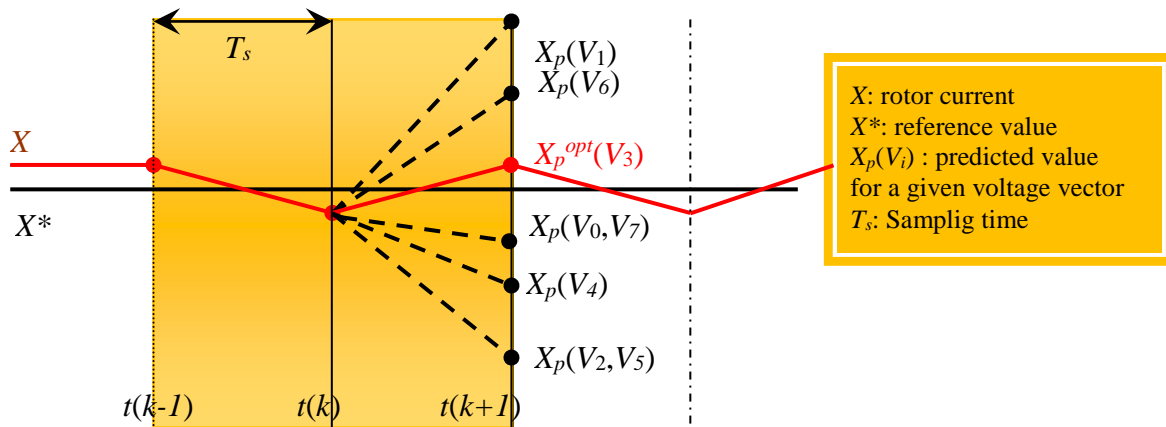

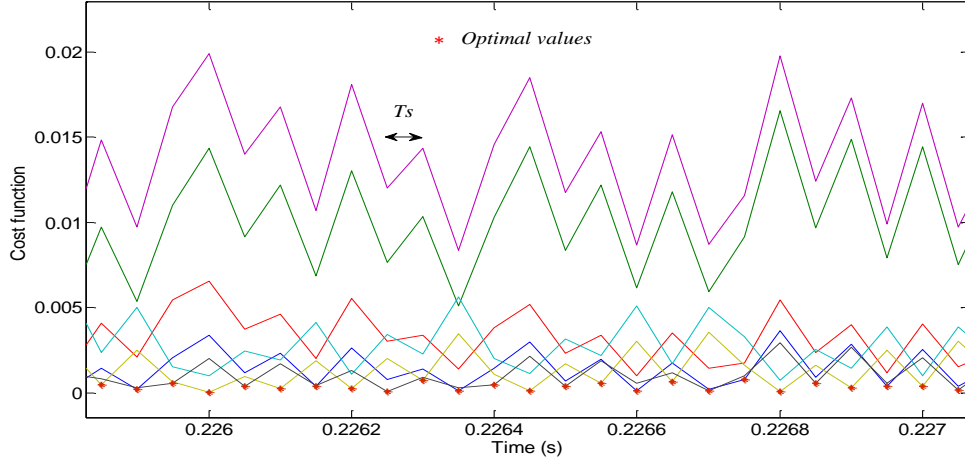Fig. 3: Selection of the optimal voltage vector in a two-level voltage source inverter with FS-MPC control

Fig. 4: Cost function optimization

The flow chart of the proposed predictive control is given by fig. 5, where for each voltage vector the cost function G_i is evaluated and the voltage vector that minimizes the cost function is then applied during the next sampling period according to the receding horizon control as can be shown in fig.4.
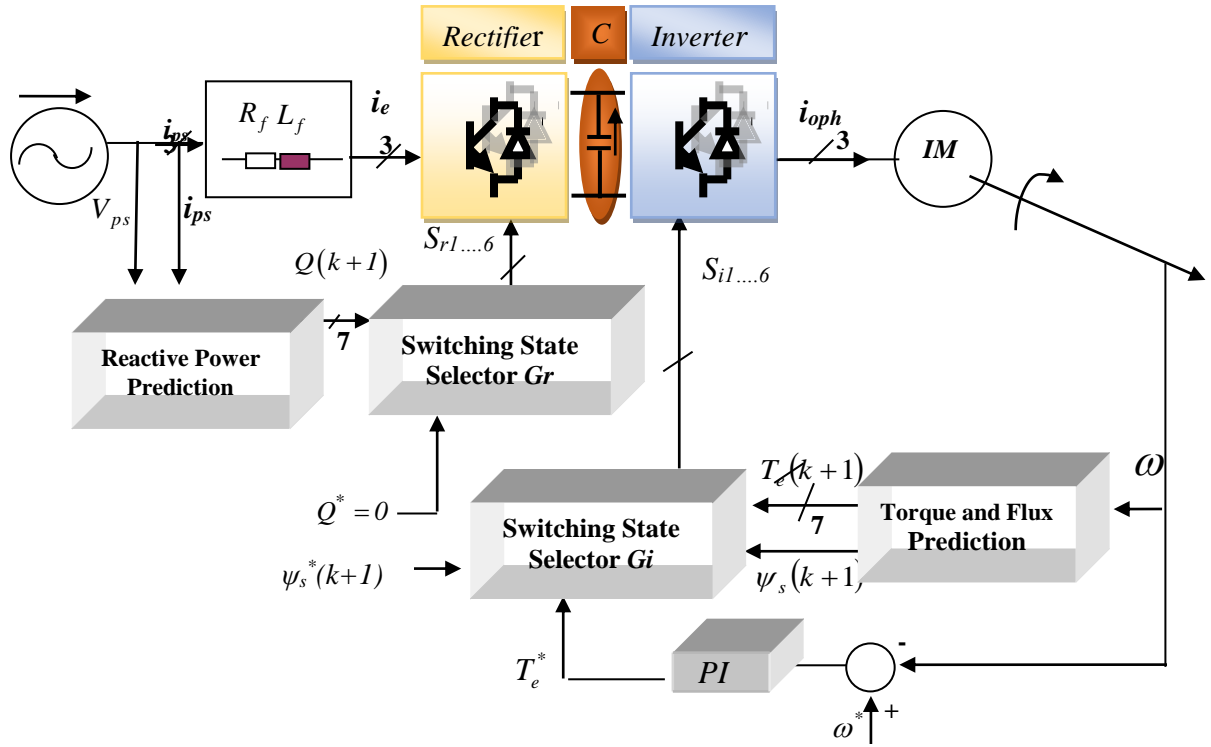

Fig.5: Predictive Indirect Power Control (AC/DC/AC) with energy storage scheme

II.3.2. CONTROL OF THE RECTIFIER SIDE

The purpose of the rectifier control is the possibility to control the displacement factor in the supply voltage side by minimizing the input reactive power (fig.6). In this case, this objective can be obtained by minimizing the predicted instantaneous power factor, which is given by the error between the reference and the predicted value of the instantaneous reactive power is given by :

$$G_r = \eta * \left| Q^*(k+1) - Q(k+1) \right| \tag{6}$$

where α, β, η are the weight coefficients which denotes the priority in the control. Finally, the instantaneous reactive input power can be predicted, based on predictions of the input current, as [7]:

$$Q(k+1) = v_{s\beta}(k+1)i_{s\alpha}(k+1) - v_{s\alpha}(k+1)i_{s\beta}(k+1) \tag{7}$$
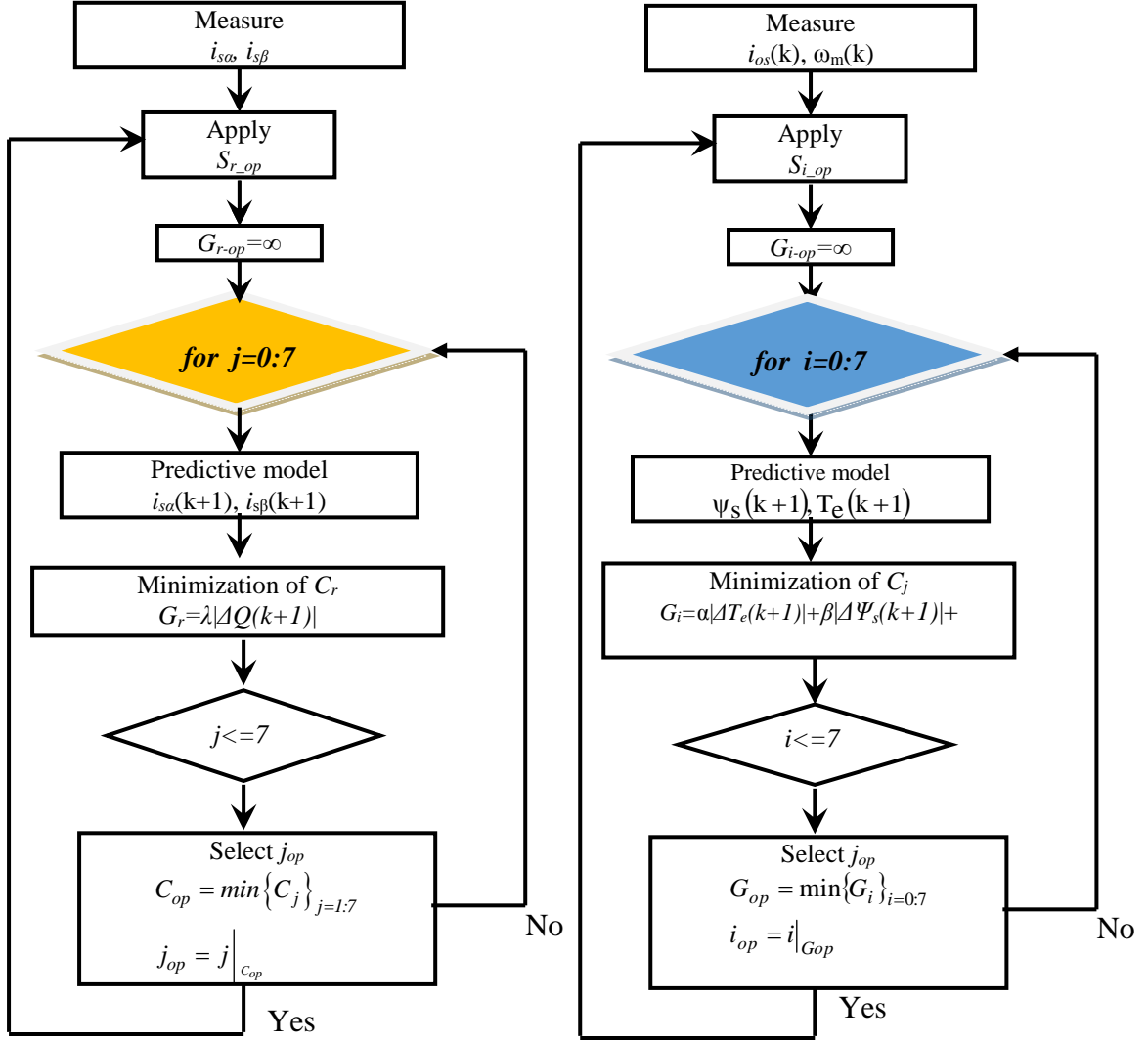
(a) Predictive algorithm for the Rectifier

(b) Predictive algorithm for the Inverter

Fig. 6: Flow chart of the predictive algorithm for Indirect Converter (AC/DC/AC).

III. Indirect matrix converter without energy storage

Derived from the indirect transfer function approach, the indirect matrix converter consists of a current source rectification stage and a voltage source inversion stage [8].

The converter topology is shown in Fig. 7, and it consists of a rectifier connected to the inverter through a dc-link without energy storage element. The converter synthesizes a positive voltage in the dc-link by selecting a switching state in the rectifier that connects one phase to the point P and the other phase to the point N. In addition, the rectifier includes an LC filter in the input side which is needed to prevent over voltages and to provide filtering of the high frequency components of the input currents produced by the commutations and the inductive nature of the load [9].

The dc-link voltage v_{dc} is synthesized by the input voltages $\mathbf{v}_i = [v_{iA} \ v_{iB} \ v_{iC}]$ and the switching states as follow:

$$v_{dc} = \begin{bmatrix} S_{rA} - S_{rA}^* & S_{rB} - S_{rB}^* & S_{rC} - S_{rC}^* \end{bmatrix} v_i \tag{8}$$

where $S_{rA}.....\ S_{rC}^*$ are the switching states of the rectifier stage.

In addition, the input current $i_i = [i_{iA}\ i_{iB}\ i_{iC}]$ T is doing by the switching state and the dc-link current i_{dc}, as:

$$i_i = \begin{bmatrix} S_{rA} - S_{rA}^* \\ S_{rB} - S_{rB}^* \\ S_{rC} - S_{rC}^* \end{bmatrix} i_{dc} \tag{9}$$

The dc-link current i_{dc}, is determined by the switching states of the inverter stage $S_{ia}\dots S_{ic}^*$, and the output current i_o =$[i_{oa}\ i_{ob}\ i_{oc}]^{\text{T}}$ as follows:

$$i_{dc} = \begin{bmatrix} S_{ia} & S_{ib} & S_{ic} \end{bmatrix} i_o \tag{10}$$

The output voltage $v_o = [v_{oa}\ v_{ob}\ v_{oc}]^{\text{T}}$ is determined by the switching states of the inverter stage and the dc-link voltage v_{dc} as:

$$v_o = \begin{bmatrix} S_{ia} - S_{ia}^* \\ S_{ib} - S_{ib}^* \\ S_{ic} - S_{ic}^* \end{bmatrix} v_{dc} \tag{11}$$
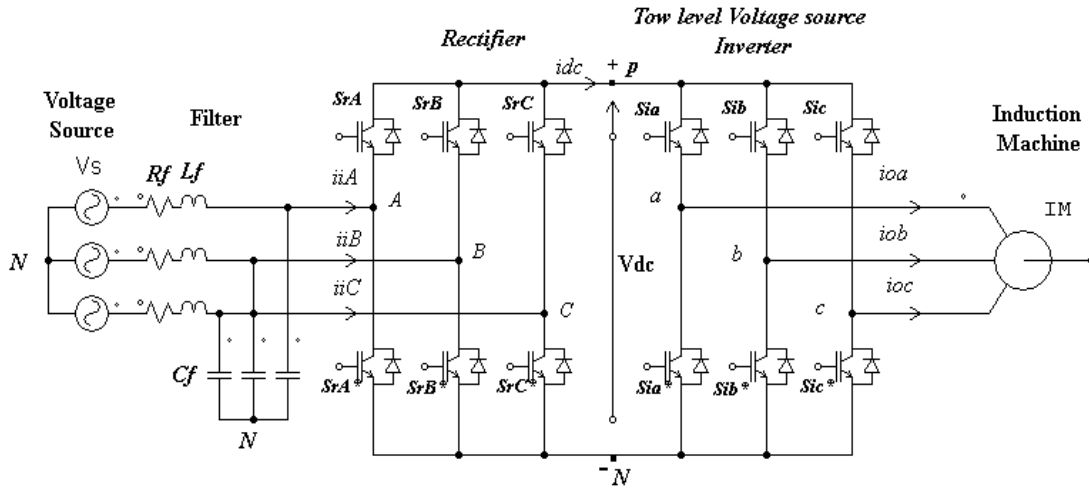

Fig. 7: Indirect Matrix Converter without energy storage (IMC)
power topology.

The rectifier and inverter stages have 8 and 9 different possible switching states respectively [9].

III.1. Induction motor model

A squirrel cage induction motor model fed by a IDMC converter is used under simplified assumptions where iron saturation, skin effect, heating variations of stator and rotor resistances are neglected. The model is expressed in the (α-β) reference frame where outputs are stator currents and fluxes, the state variables are rotor fluxes and stator currents as follows:

$$\begin{cases} V_s = R_s i_s + \dfrac{d\psi_s}{dt} \\[2mm] 0 = R_r i_r + \dfrac{d\psi_r}{dt} - j\,\omega_m\,\psi_s \\[2mm] \psi_s = L_s i_s + L_m i_r \\[2mm] \psi_r = L_m i_s + L_r i_r \end{cases} \tag{12}$$

$$T_e = \frac{3}{2} p\,\psi_s\,i_s \tag{13}$$

$$\psi_s = \sigma L_s i_s + \frac{L_m}{L_r}\psi_r \tag{14}$$

Where (R_s, R_r) are stator and rotor resistance per phases respectively, (i_s, i_r) are stator and rotor current vectors, (ψ_s, ψ_r) are stator and rotor fluxes vectors respectively, (L_s, L_r, L_m) are stator, rotor and mutual inductances, ω_m is the rotor speed, T_e is the electromagnetic torque of the machine and p is the number of pair poles. Based on equations (12) and (14), one can represent the dynamical model as [9]:

$$\frac{d}{dt}\begin{pmatrix} i_s \\ \psi_r \end{pmatrix} = \begin{pmatrix} -\dfrac{1}{\tau_\sigma} & \dfrac{k_r}{\tau_\sigma R_\sigma}\left(\dfrac{1}{\tau_r} - j\omega_m\right) \\[3mm] \dfrac{L_m}{\tau_r} & -\dfrac{1}{\tau_r} + j\omega_m \end{pmatrix}\begin{pmatrix} i_s \\ \psi_r \end{pmatrix} + \begin{pmatrix} \dfrac{1}{\tau_\sigma R_\sigma} \\[3mm] 0 \end{pmatrix} V_s$$

$$\psi_s = \begin{pmatrix} \sigma L_s & \dfrac{L_m}{L_r} \end{pmatrix}\begin{pmatrix} i_s \\ \psi_r \end{pmatrix} \tag{15}$$

Under state space form:

$$\dot{X} = AX + BU, \quad Y = CX$$

$$X = \begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{pmatrix}, \quad U = \begin{pmatrix} V_{s\alpha} \\ V_{s\beta} \end{pmatrix}, \quad Y = \begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{sd} \\ \psi_{sq} \end{pmatrix} \tag{16}$$

Separating real and imaginary components of equations (8), one can obtain:

$$A = \begin{pmatrix} -\dfrac{1}{\tau_\sigma} & 0 & \dfrac{k_r}{\tau_\sigma R_\sigma \sigma_r} & \dfrac{k_r \omega_m}{\tau_\sigma R_\sigma} \\[3mm] 0 & -\dfrac{1}{\tau_\sigma} & -\dfrac{k_r}{\tau_\sigma R_\sigma}\omega_m & \dfrac{k_r}{\tau_\sigma R_\sigma \sigma_r} \\[3mm] \dfrac{L_m}{\tau_r} & 0 & -\dfrac{1}{\tau_r} & -\omega_m \\[3mm] 0 & \dfrac{L_m}{\tau_r} & \omega_m & -\dfrac{1}{\tau_r} \end{pmatrix} \tag{17}$$

$$B = \begin{pmatrix} \dfrac{1}{\tau_\sigma R_\sigma} & 0 \\[3mm] 0 & \dfrac{1}{\tau_\sigma R_\sigma} \\[3mm] 0 & 0 \\[3mm] 0 & 0 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & 0 & 0 & 0 \\[2mm] 0 & 1 & 0 & 0 \\[2mm] \sigma L_s & 0 & \dfrac{L_m}{L_r} & 0 \\[3mm] 0 & \sigma L_s & 0 & \dfrac{L_m}{L_r} \end{pmatrix} \tag{18}$$

III.2 . Predictive torque and flux control

Based on a given stator component voltage vector $V_{si}(k)$, measured current $i_s(k)$ and estimated rotor flux $\psi_r(k)$ at current sampling instant, it is possible to obtain one step ahead prediction of stator current $i_s(k+1)$ and rotor flux $\psi_r(k+1)$. Also, using (13) and (14), it is possible to predict the machine torque $T_e(k+1)$ and stator flux $\psi_s(k+1)$ for this voltage vector $V_{si}(k)$. The predicted values of torque and stator flux are used to evaluate a cost function that minimizes the quadratic error between predicted values and their references. The switching state (corresponds to the optimal voltage vector) that produces the minimum value of this cost function is selected to applied on machine terminals in the next sampling time according to receding horizon control.

Prediction of stator flux, stator current and torque can be made based on previous standard estimation as:

$$\psi_s(k+1) = \psi_s(k) + T\ V_s(k+1) - R_s\ T\ i_s(k)$$
$$i_s(k+1) = \left(1 - \frac{TR_\sigma}{L_s\sigma}\right)i_s(k) + \frac{T}{L_s\sigma}\left(\left(\tau_r k_r - jk_r\omega_m\right)\psi_r(k) + V_s(k+1)\right) \qquad (19)$$
$$T_e(k+1) = \frac{3}{2}\ p\ \psi_s(k+1)\ i_s(k+1)$$

III.3. Predictive control
A. Predictive model

The rectifier and inverter stages have 9 and 8 different possible switching states respectively; altogether, the whole converter presents 72 possible switches combinations states. However, the rectifier stage can produce only positive dc-link voltage in each sampling time (3 of 9 possible switching states accomplish this request), so the number of valid switching states is 24 [2][8][10] as can be shown in fig.9

The objective control is to get high performances in term of rapid and precise dynamic torque and flux responses as in DTC control by using a quadratic cost function that minimizes the error between reference torque and flux to their computed values. The predictions on flux and torque are used to evaluate the impact of every voltage vector on motor torque and stator flux. The reference torque is generated from the external speed control loop via a simple PI controller while the flux reference is kept constant to its nominal value for normal speed operation as it is given by fig.8.
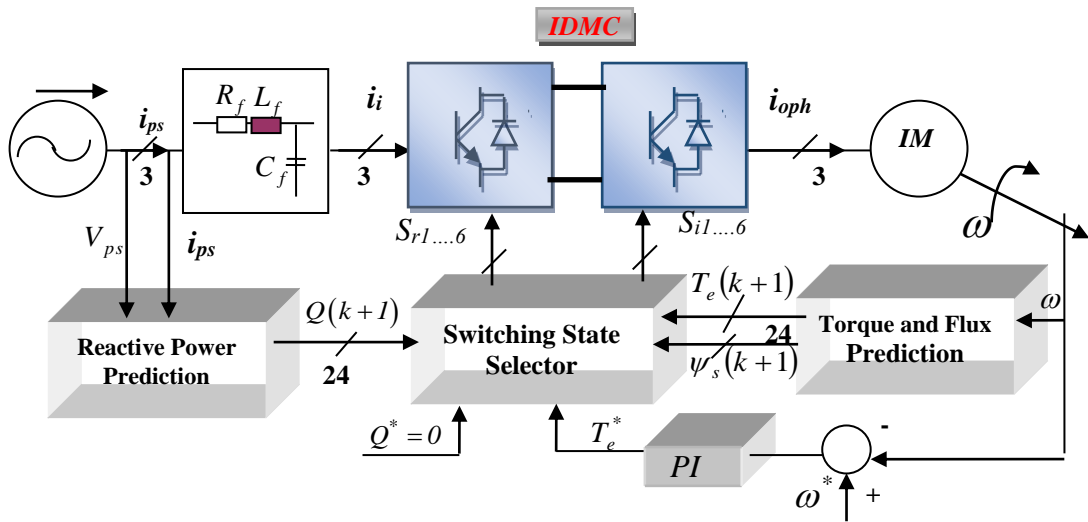

Fig.8: Predictive Indirect Power Control without energy storage scheme
(Matrix Converter)

B. Minimization of cost function

Different control criteria will be expressed in different quality function but in this work, the cost function is formulated as in [11] as:

$$G = \alpha \frac{\left(T_e^*(k+1) - T_e(k+1)\right)^2}{T_n^2} + \beta \frac{\left(\psi_s^*(k+1) - \psi_s(k+1)\right)^2}{\psi_n^2} \tag{20}$$

where T_{en} and ψ_{sn} are the nominal torque and nominal stator flux values.

One of the most benefits of IDMC converter is the possibility to control the displacement factor in the supply voltage side by minimizing the input reactive power. Multiple objectives can be achieved at the same time by adding more functions in the global cost function G as [6]:

$$G = \alpha \frac{\left(T_e^*(k+1) - T_e(k+1)\right)^2}{T_n^2} + \beta \frac{\left(\psi_s^*(k+1) - \psi_s(k+1)\right)^2}{\psi_n^2} + \lambda \left| Q^*(k+1) - Q(k+1) \right| \tag{14}$$

Where α, β, λ are the weight coefficients which denote the priority in the control.
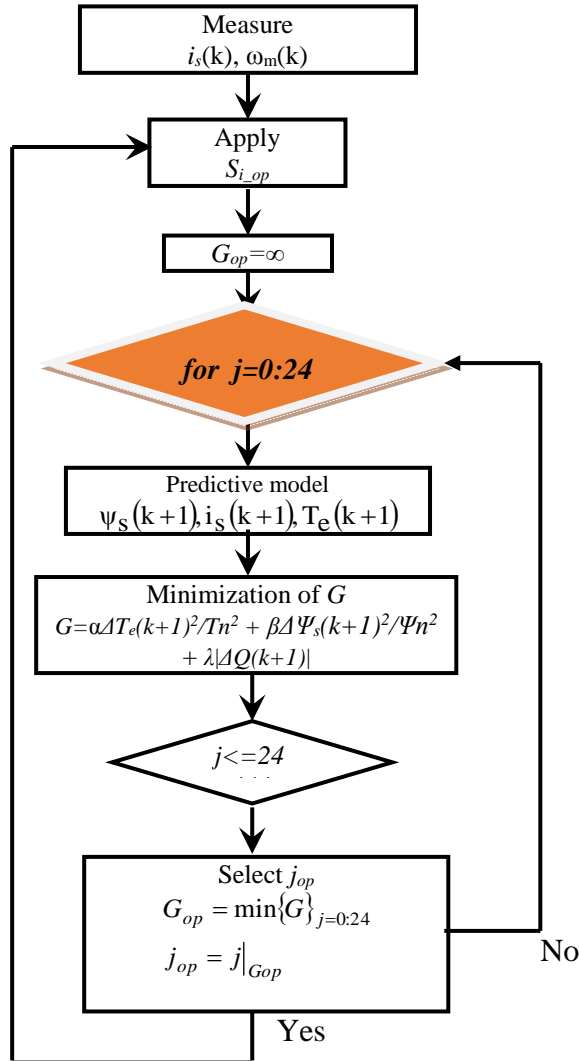

Fig. 9: Predictive control algorithm for Indirect Matrix Converter

IV .Simulation results

The proposed predictive control was simulated using Matlab. The drive is tested where the machine is running in the steady state at 50 rd/s, than a speed reversal set point of 75 rad/s is applied at 0.2s. The profile of the mechanical speed, electromagnetic torque, stator flux magnitude, output current and reactive power are visualized throw fig. 10 and fig.11.
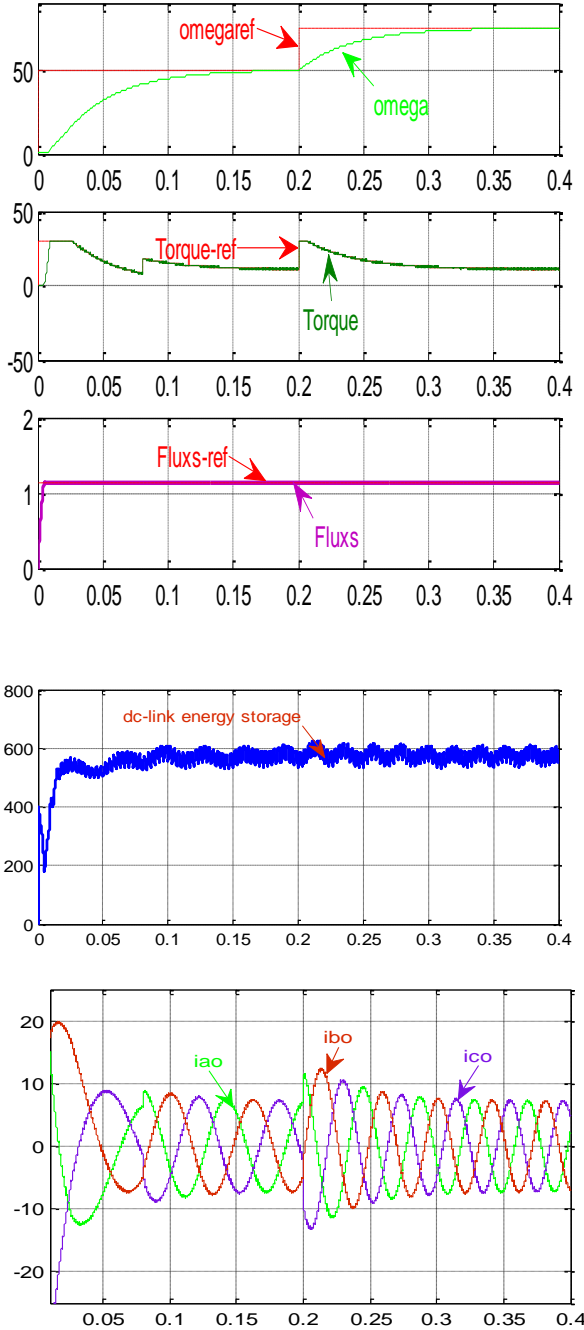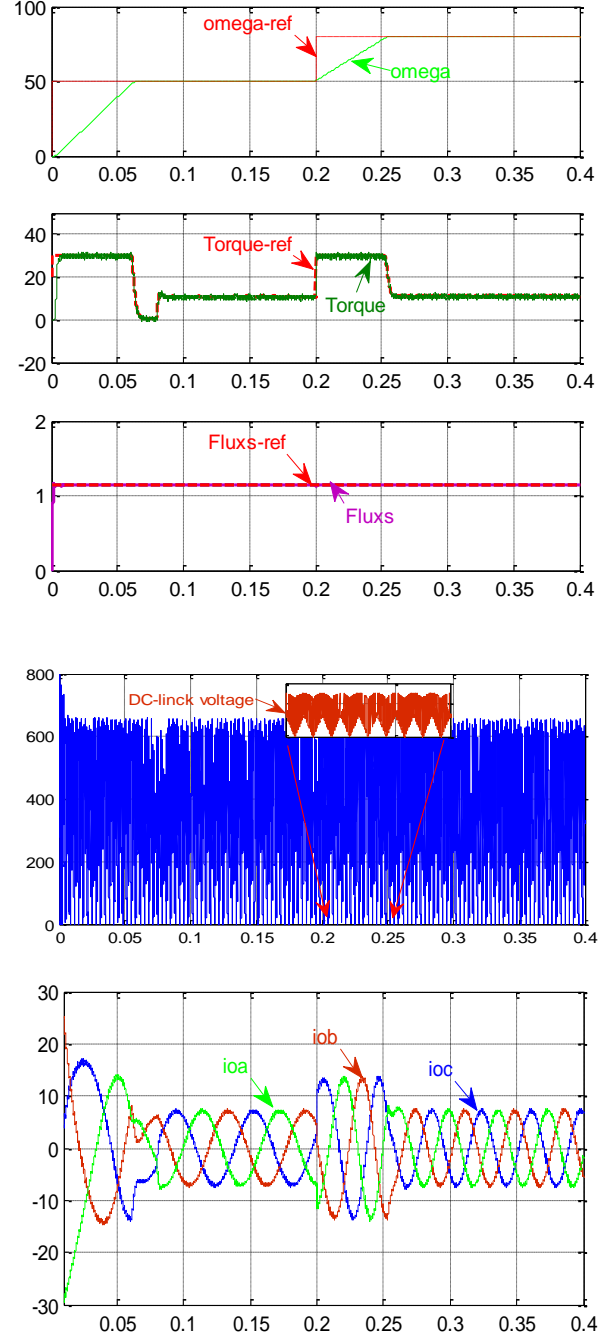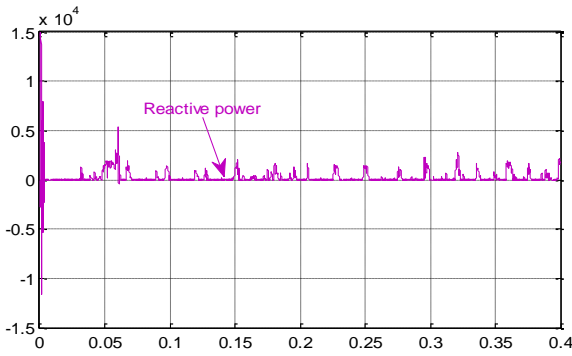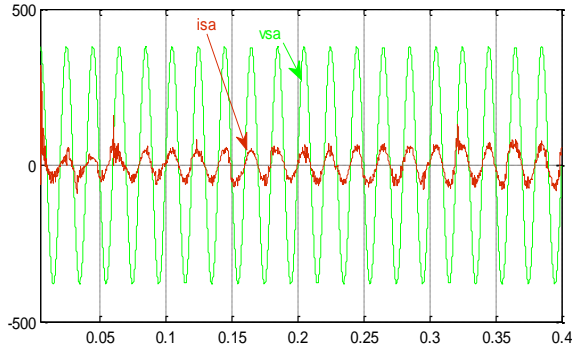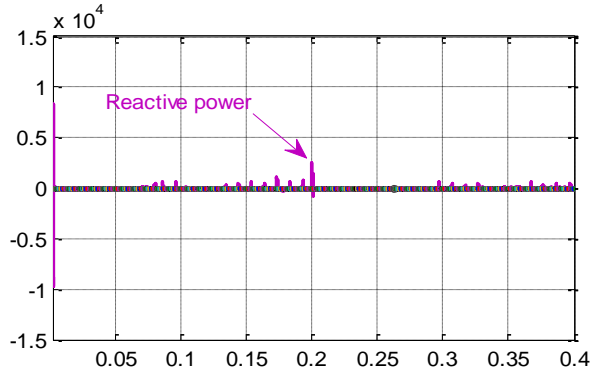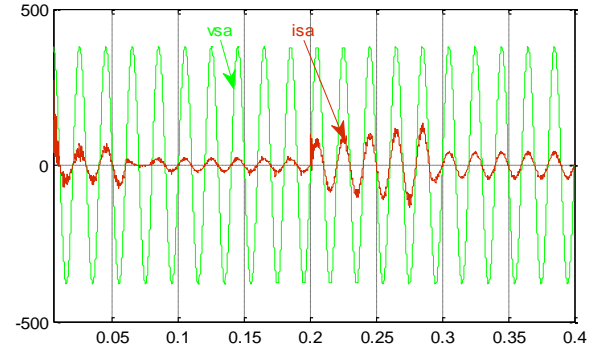

(a) FS-MPC by AC-DC-AC Converter   (b) FS-MPC by IDMC Converter

Fig.10: Simulation results for versus speed of the AC-DC-AC and IDM Converter
(ab.1) Mechanical speed, (ab.2) Electromagnetic torque, (ab.3) Stator Flux,
(ab.4) DC Voltage, (ab.5) Stator Currents

(a) FS-MPC by AC-DC-AC Converter   (b) FS-MPC by IDMC Converter

Fig.11: Simulation results with reactive power minimization of the AC-DC-AC and IDM Converter
(ab.1) Output Voltage and Current, (ab.2). Reactive Power

The simulation parameters are indicated in Table I and the sampling period of the control algorithm was set in T_s = 10 μs. The control of torque, flux and the minimization of the reactive power in the input system. Both test considers the starting of the induction machine at t = 0.05s without a load torque, applying a speed reference change from 50 rad/s to 75 rad/s; during the starting, the torque of the machine is limited at its nominal value 30 Nm. In the instant t = 0.08s is applied a load torque equal to 10 Nm.

Tab. I: Main circuit parameters

C_f , L_f, R_f	90 μF , 400 μH , 0.5 Ω
Ts(sampling time)	10 μs
Weighting factors	$\alpha = 1000$, $\beta = 15000$, $\lambda = 0$ or 0.0365
Machine parameters	T_{en}=30N.m; ψ_{sn} =1.14Wb; J=0.035(USI); R_r=1.83 Ω ; R_s=0.97 Ω ; lr=0.165H; ls=0.161H; p=2; ff=0.01(USI); Tr=lr/Rr; M=0.154H

Fig. 10 shows that the torque presenting a very good dynamic and precise response and it is completely separated from the stator flux which is kept constant during dynamic transitions. The load current appears highly sinusoidal, although no current controllers are used in the control algorithm.

The reactive power minimization is included in the cost function of (6) for AC-DC-AC Control and in the cost function of (14) for IDMC control where the reactive power reference is set to 0, on fig.11, we can see that sinusoidal input current in phase with supply voltage is achieved during motoring operation of the drive. Actually we can find that`s the unity power fact is more clear in figure b.

The drive is tested in a four quadrant (4Q) operational capability where the machine is running in the steady state at 50 rad/s, than a speed reversal set point of −50 rad/s. The test considers the starting of the induction machine at t = 0.06s without a load torque, applying a speed reference change from 0 to 50 rad/s; during the starting, the torque of the machine is limited at nominal value 30 Nm. In the instant t= 0.08s is applied a load torque equal to 10 Nm and on this moment the reversing introduced in t = 0.16s (changing the speed reference from 50 rad/s to -50 rad/s). Finally we have applied a load torque equal to -10 Nm at instant t = 0.34s. The torque reference has generated by the speed controller is different from zero during the transients and load torque steps and can appreciate a good tracking of the speed (Fig. 12.a), torque (Fig. 12.b) and stator flux (Fig. 12.c) to their references.
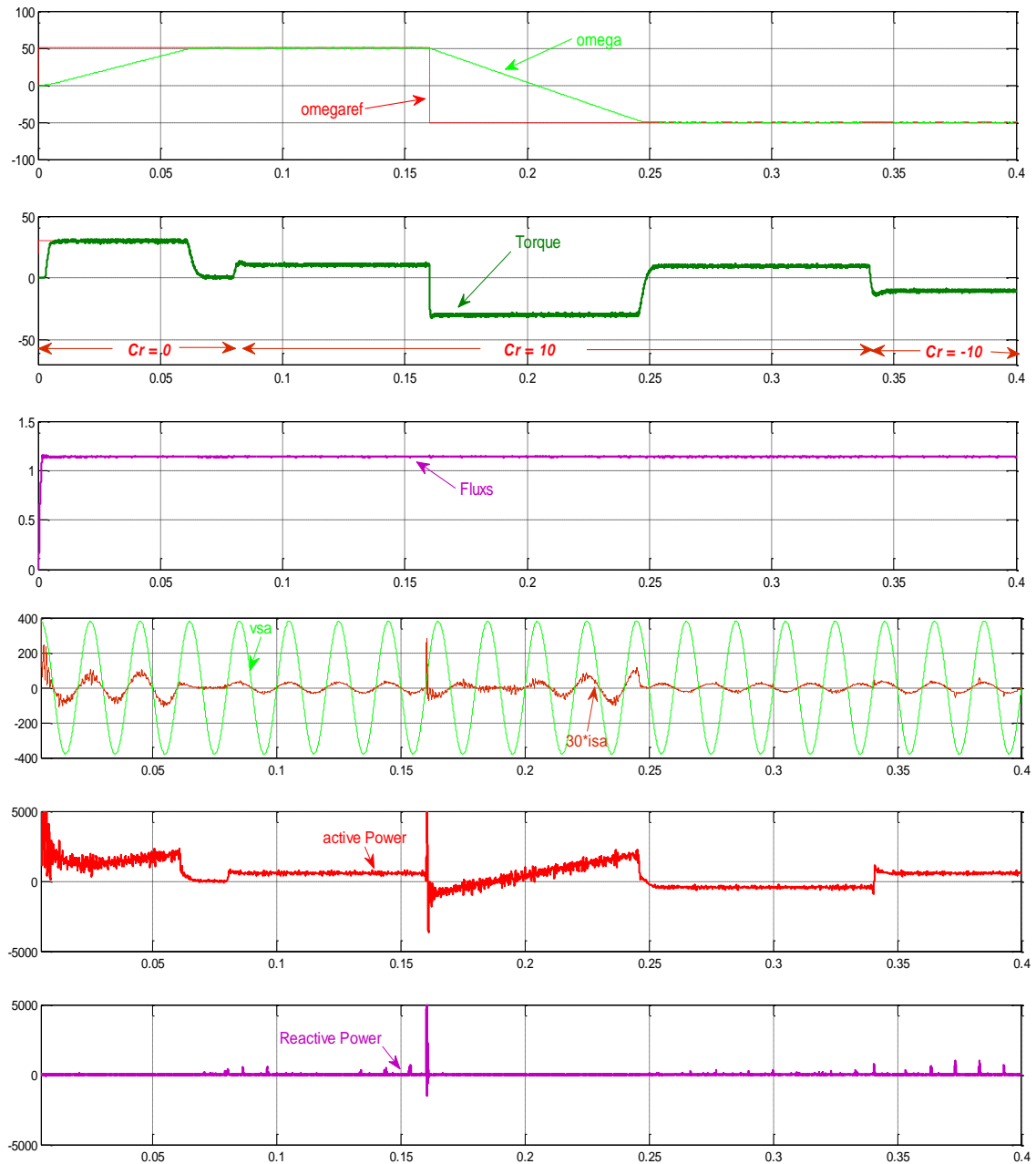

Fig.12: Simulation results of the indirect converter without energy storage during four quadrant
(a) Mechanical speed, (b) Electromagnetic Torque, (c) Stator Flux,
(d) Output Voltage and Current, (e) Active Power, (f) Reactive Power

From Figure 12, one can see that sinusoidal input current in phase with supply voltage is achieved during motoring operation of the drive. When the drive operates to regenerate energy (regenerating mode), it is also observed that sinusoidal input current is also achieved with π rad phase shift with the phase voltage, making the energy flows from the motor to the mains (regenerating) possible.

V. Conclusion

A very effective predictive torque and flux control method with reactive power minimization are applied in an indirect converter have been presented in this work. The strategy offers the possibility to control both the torque and flux, also to maintain unity power factor, and the output voltage or mechanical speed at the same time. The control scheme uses a discrete model of the converter. With DC-link energy, storage converter, the quality function is to minimize the error between reference and actual torque, flux for the inverter. The rectifier control is to regulate the DC-link voltage while having sinusoidal input currents in phase with their respective supply line voltages (unity power fact). For indirect converter without DC-link energy storage the ideal minimum of the cost function is zero and it represents the perfect regulation of the controlled variables. These results show that predictive control is very powerful method. Because it provides a good tracking property and high performance for both motoring and regeneration modes capability of the drive system. To conclude, Finite States Predictive Control fed by an Indirect Converter is a very promising alternative for the future of power electronics.

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