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# Predictive Control fed by an Indirect Converter with and without energy storage using PSO Optimization

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**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 inverter) 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 is then applied to the output of the power converter. The main aim of this paper is to propose an online optimization of the weighting factors by the Particle Swarm Optimization (PSO) approach well known by its robustness and fast convergence to the global optimum. Simulation results show that PSO strategy is very efficient to design accurately and quickly these weighting factors.



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## 1. 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 extensive1 ly used in 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. In addition, 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 [1] 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]. The method is based on the fact that a finite number of possible switching states can be generated by power converter 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. [3]. used cost functions include generally two terms or more. These terms are penalized by weighting factors that decide whether the priority is given to the states which minimize the errors in these terms. In [4], the authors were used a quality function that contains three terms for output currents and reactive power minimization in the supply side where they said that an exhaustive search was carried out based on 400 simulations, each with a value of weighting factor equidistant within the range [0 - 0.007] V−1 which is considered as a hard task. In [5], [6], the torque and stator flux errors with reactive power minimization were used as the three terms of the quality function. Once again, it was observed that the determination of weighting parameter was a tough task. The present paper proposes a design procedure of an online particle swarm weighting factor optimization method well suited for predictive direct torque and flux control.

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, 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. In this paper, we investigate the performance of particle swarm optimization for optimizing weighting factor procedure and then we carried out some simulation results to validate the proposed control method in the sixth section followed at last by a general conclusion.

## 2 . 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 Figure 1 is considered. For a simpler analysis, the converter can be separated mainly in rectifier and inverter sides.

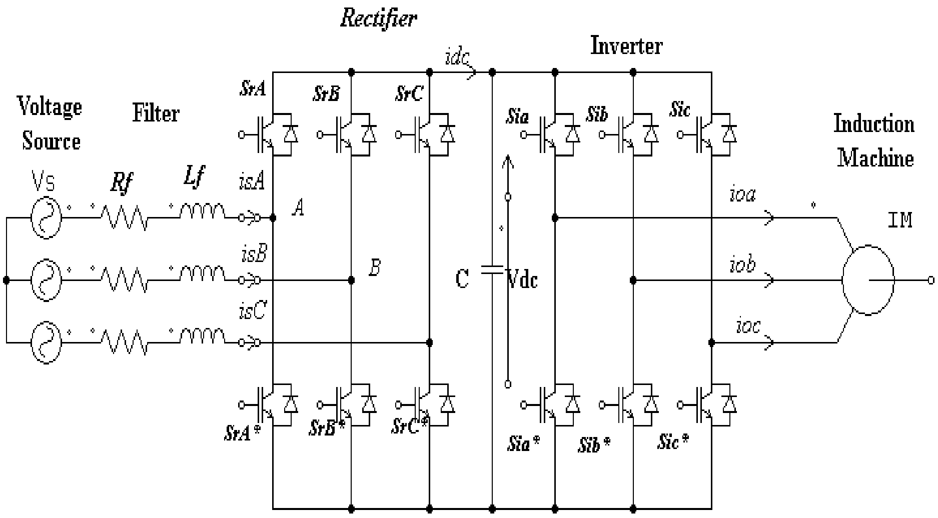



Figure 1. Indirect Converter (AC/DC/AC) power topology With energy storage

### 2.1. 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 by equation:

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

where $\boldsymbol{i}_s$ is the input current vector, $\boldsymbol{V}_s$ is the supply line voltage and $\boldsymbol{V}_{rec} = \boldsymbol{S}_r * V_{dc}$ is the voltage generated by the converter. The input current vector is related to the phase currents by the equation:

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

$\boldsymbol{S}_r$ 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.

**2.2. Inverter side**

For a two level voltage source inverter feeding a symmetrical three-phase induction motor given in figure 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 $\boldsymbol{V}_{inv}$ is linked to the inverter switching state $\boldsymbol{S}_i$ : $\boldsymbol{V}_{inv} = \boldsymbol{S}_i V_{dc}$ .

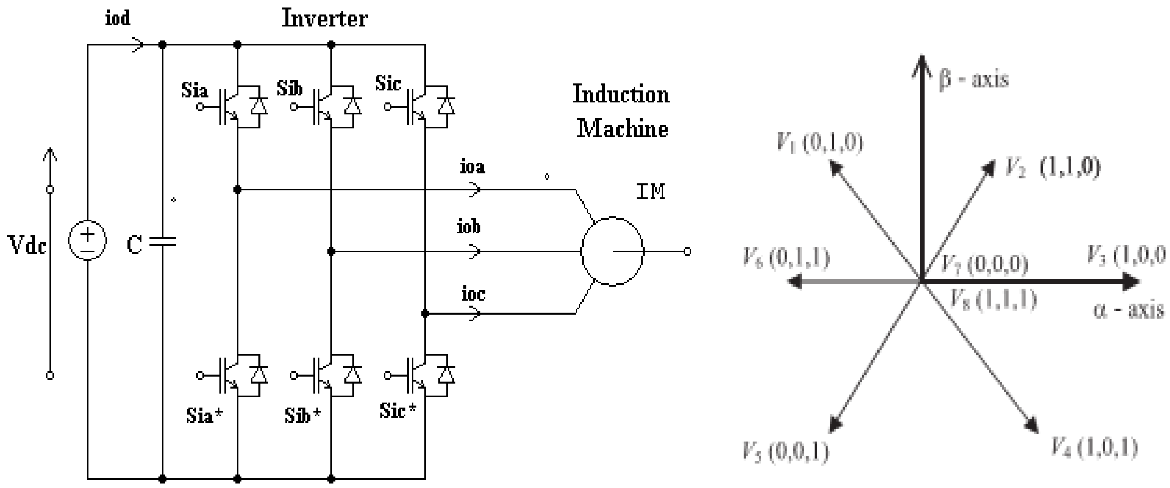



Figure 2. Two level source inverter with different voltage vectors

**2.3. Minimization of cost function**

**2.3.1. 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 [8][14]as can be shown in fig.3. 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

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

where $T_n$ and $\psi_n$ are the nominal torque and nominal stator flux values, and $\alpha,\beta,\lambda$ are the weight coefficients which denotes the priority in the control.

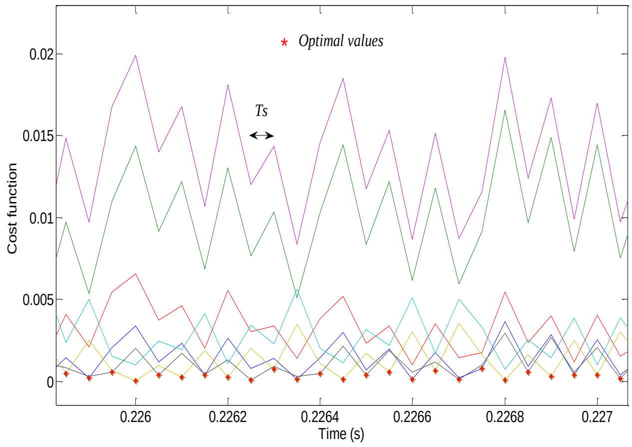



Figure 3. Selection of the optimal voltage vector for Cost function optimization in a two-level Voltage source inverter with FS-MPC control

### 2.3.2. 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.4.a). 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:

$$G_r = \lambda * \left| Q^*(k+1) - Q(k+1) \right| \quad (6)$$

where $\alpha,\beta,\eta$ 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 [9]:

$$Q(k+1) = v_{s\beta}(k+1) i_{s\alpha}(k+1) - v_{s\alpha}(k+1) i_{s\beta}(k+1) \quad (7)$$

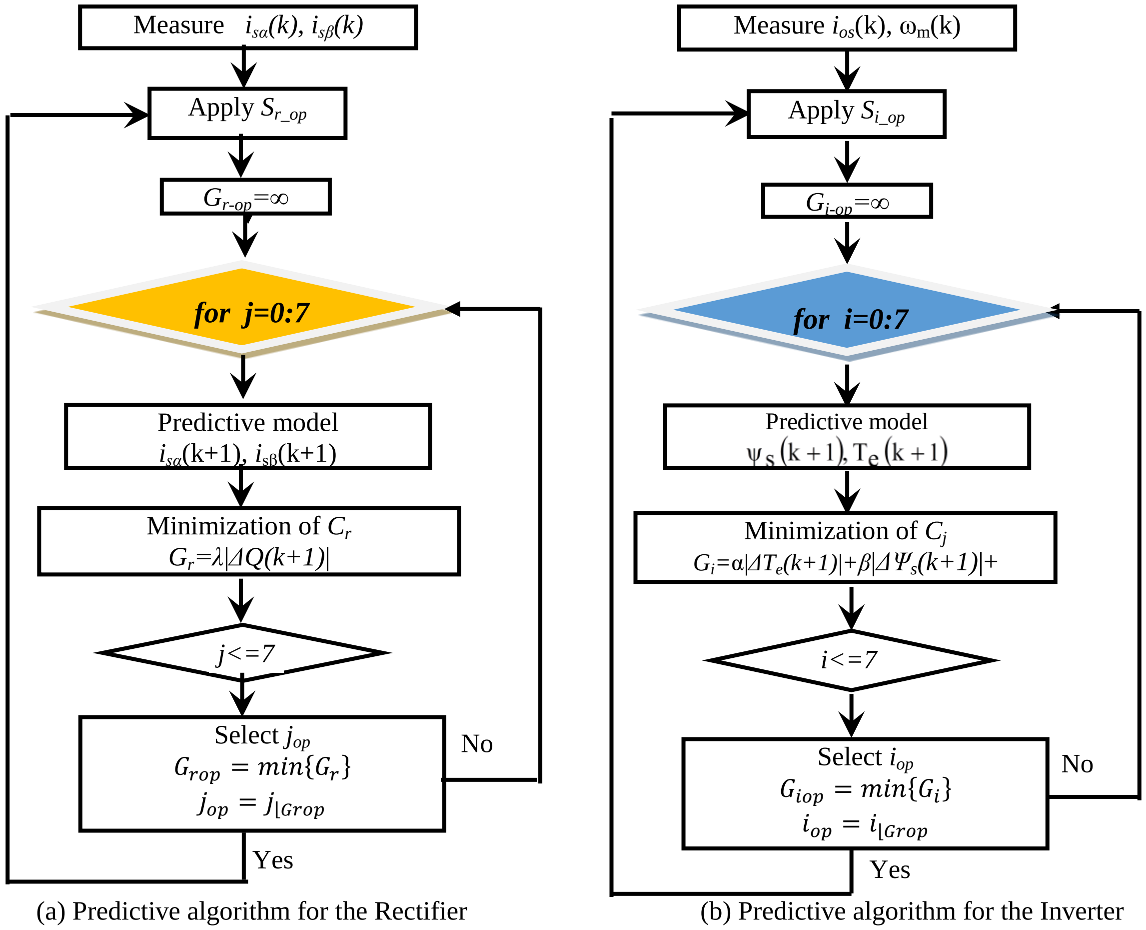



Figure 4. Flow chart of the predictive algorithm.

### 3.1. Induction motor model

A squirrel cage induction motor model fed by a Indirect 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:

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

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

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

Where ($R_s$, $R_r$) are respectively stator and rotor resistance per phase, ($i_s$, $i_r$) are stator and rotor current vectors, $(\psi_s, \psi_r)$ are stator and rotor flux vectors respectively, $(L_s, L_r, L_m)$ are stator, rotor and mutual inductances,

$\omega_m$ 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 [10]:

$$\frac{d}{dt}\begin{pmatrix} i_s \\ \psi_r \end{pmatrix} = \begin{pmatrix} -\frac{1}{\tau_\sigma} & \frac{k_r}{\tau_\sigma R_\sigma}\left(\frac{1}{\tau_r} - j\omega_m\right) \\ \frac{L_m}{\tau_r} & -\frac{1}{\tau_r} + j\omega_m \end{pmatrix}\begin{pmatrix} i_s \\ \psi_r \end{pmatrix} + \begin{pmatrix} \frac{1}{\tau_\sigma R_\sigma} \\ 0 \end{pmatrix} V_s \qquad (15)$$

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

## 3.2. 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 $\psi_r(k+1)$. In addition, 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 and 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:

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

The flow chart of the proposed predictive control is given by figure 5

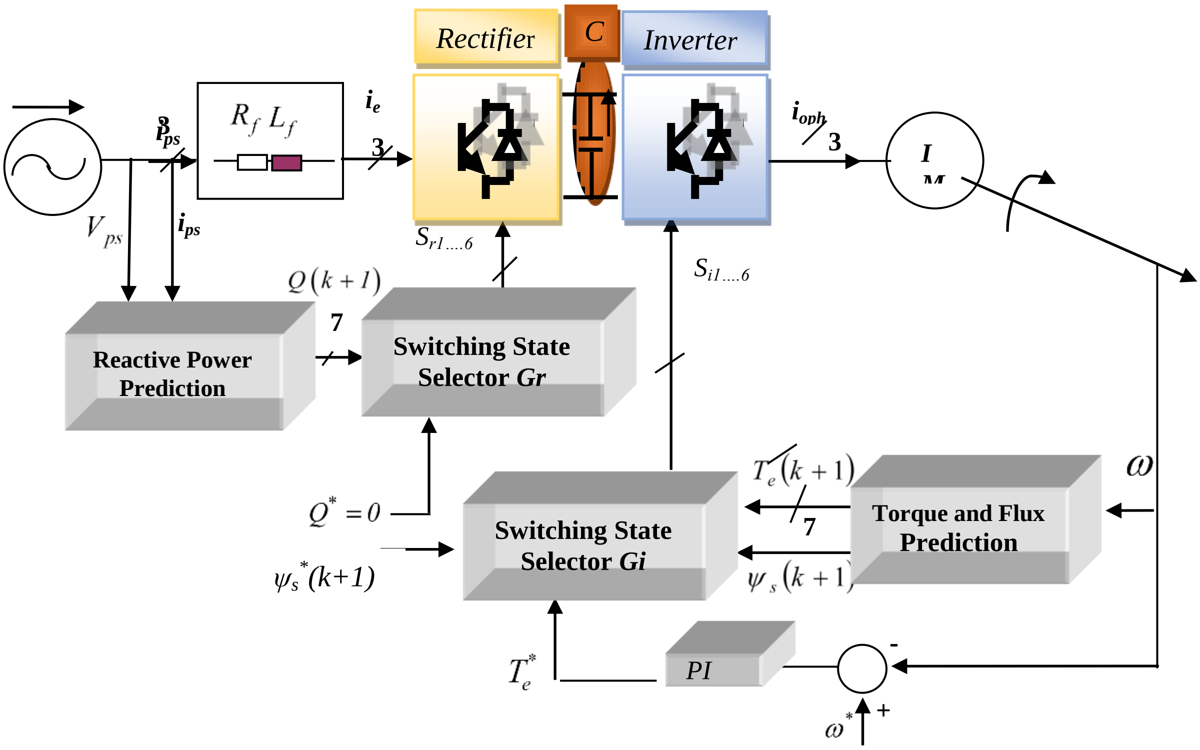



Figure 5. Predictive Indirect Power Control P-IPC control scheme with energy storage

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 figure 4.

## 3. 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 [9].

The converter topology is shown in Fig. 6, 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 [11]. The dc-link voltage $v_{dc}$ is synthesized by the input voltages $\boldsymbol{v_i}$ = [$v_{iA}$ $v_{iB}$ $v_{iC}$] and the switching states as follow:

$$v_{dc} = \left[S_{rA} - S_{rA}^* \quad S_{rB} - S_{rB}^* \quad S_{rC} - S_{rC}^*\right] v_i \tag{8}$$

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 theswitching 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 $S_{ia}$… $S_{ic}^*$, and the output current $i_o$ =[$i_{oa}$ $i_{ob}$ $i_{oc}$]$^T$ as follow:

$$i_{dc} = \left[S_{ia} \quad S_{ib} \quad S_{ic}\right] i_o \tag{10}$$

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

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

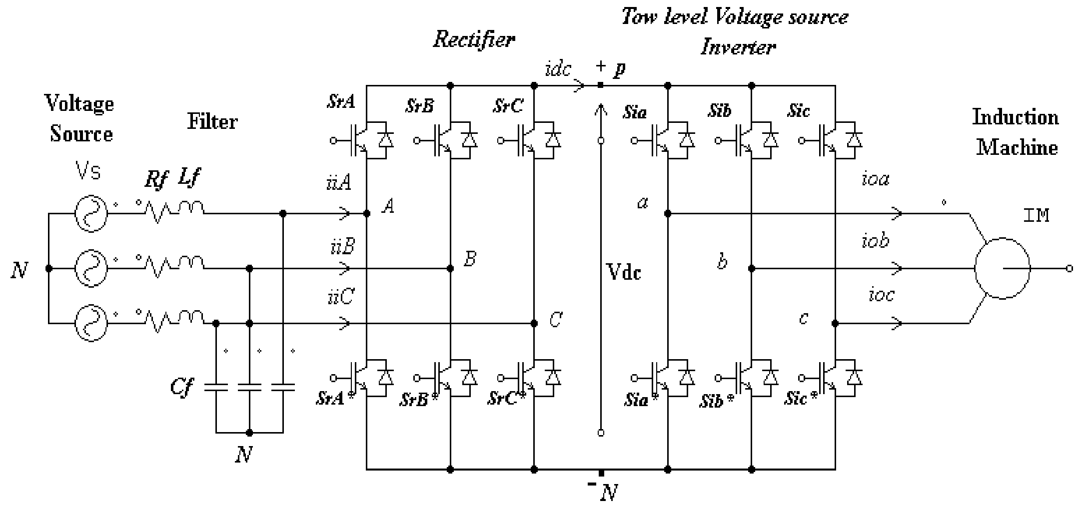


Figure 6. Indirect Matrix Converter (IMC) power topology.

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

### 3.3. Predictive control

#### 3.3.1. 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 [12][9][5] as can be shown in figure 7.

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 figure 8.

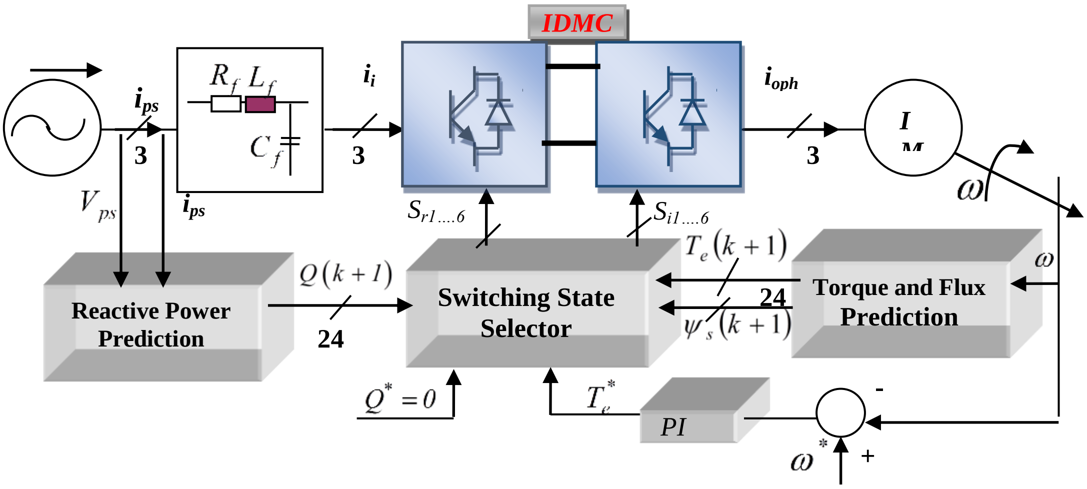



Figure 7. Predictive Indirect Power Control P-IPC control scheme without energy storage (Matrix Converter)

#### 3.3.2. Minimization of cost function

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 [10] [13] T.he cost function must consider the objectives of control, in this case the generation of unity power factor and the control of the torque and flux:

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

where $\alpha, \beta, \lambda$ are the weight coefficients which denotes the priority in the control.

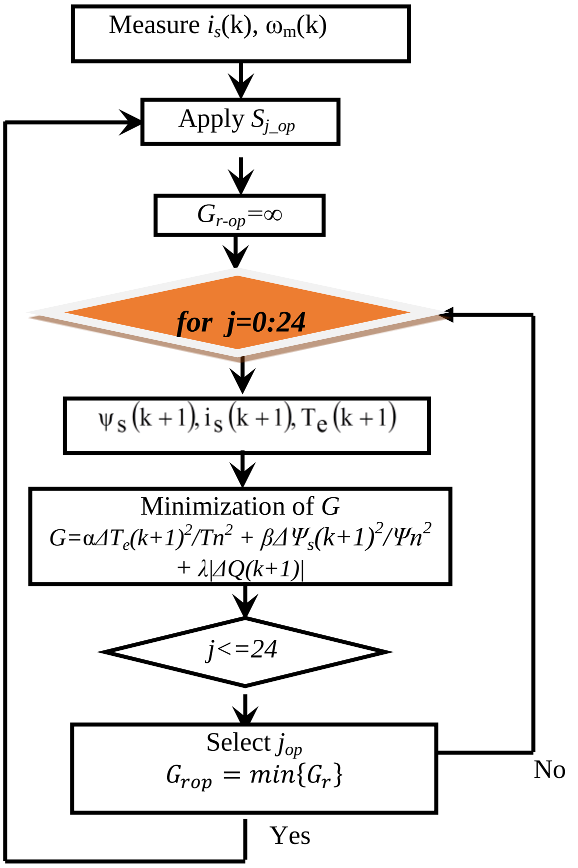


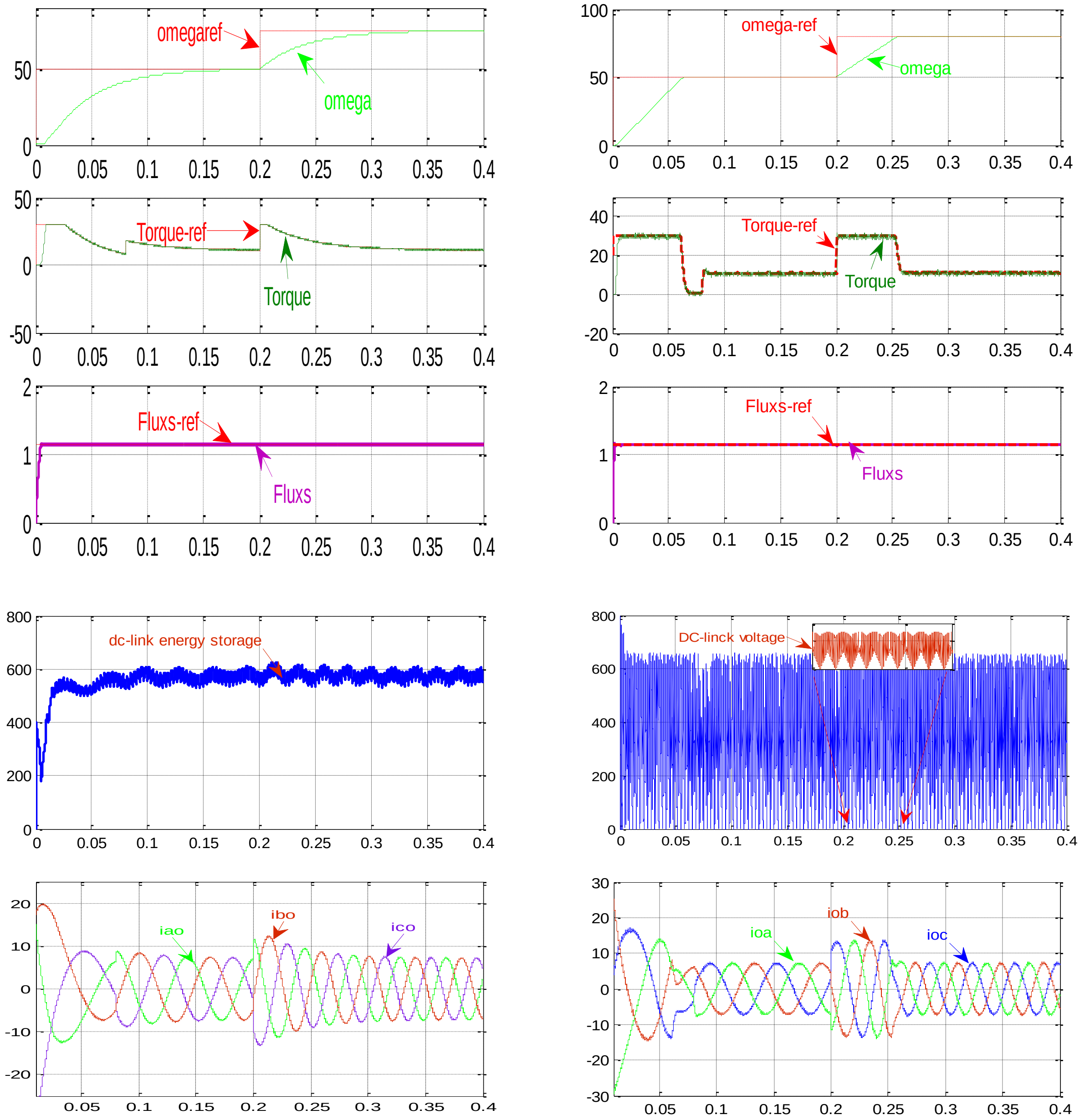

Figure 8. Predictive control algorithm with Indirect Matrix Converter

## 4. SIMULATION RESULTS

The proposed predictive control is tested via simulation on the bench of figure 9-10 with a sampling time of 10 $\mu s$ and the simulation parameters are indicated in Table 1.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 load torque, mechanical speed, electromagnetic torque, stator flux magnitude and output current are visualized throw figure 9 and figure 10.

Table 1. Main circuit parameters

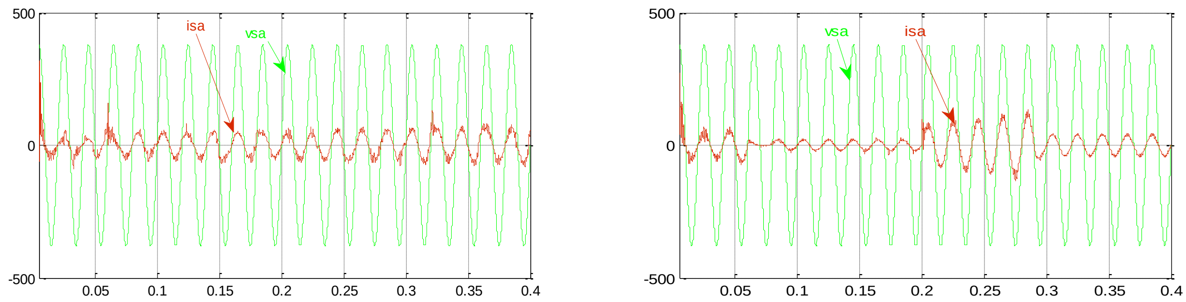
| | |
|---|---|
| $C_f$ , $L_f$, $R_f$ | 90 $\mu F$ , 400 $\mu H$ , 0.5 $\Omega$ |
| Ts(sampling time) | 10 $\mu s$ |
| Weighting factors | $\alpha=1000$, $\beta=15000$, $\lambda=0$ or 0.0365 |
| Machine parameters | $T_{en}$=30N.m; $\psi_{sn}$ =1.14Wb; J=0.035(USI); $R_r$=1.83 $\Omega$ ; $R_s$=0.97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

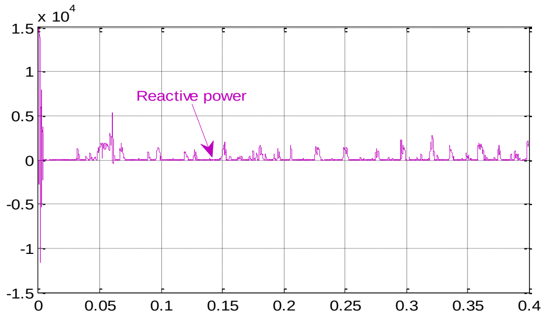



(a) FS-MPC by AC-DC-AC Converter (b) FS-MPC by IDMC Converter

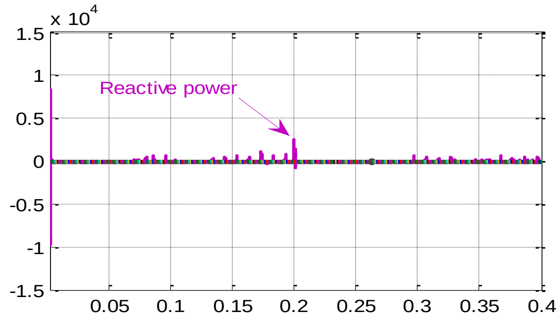
Figure 9. Simulation resultat for versus speed of the AC-DC-AC and IDM Converter

(ab.1) Electromagnetic torque, (ab.2) stator flux, (ab.3) DC-link voltage, (ab.4) Stator currents






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




(b) FS-MPC by IDMC Converter

Figure 10. 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 1 and the sampling period of the control algorithm was set in $T_s$ = *10 μs*. Tthe 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 to 75; 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.

Figure 9 shows that the torque presents a very good dynamic and precise response and it is completely decoupled from the stator flux that is kept constant at all times during dynamic transitions. The load currents appear 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 (6) for IDMC control. The reactive power reference is set to 0 in order to make input current in phase with the supply voltage. On figure 10, one can see that sinusoidal input current in phase with supply voltage is achieved during motoring operation of the drive.

## 5. PARTICLE SWARM OPTIMIZATION WEIGHTING *(PSO)* FACTOR OPTIMIZATION

Particle swarm optimization (PSO) is a population-based optimization method first proposed by Kennedy and Eberhart in 1995, inspired by social behavior of bird flocking or fish schooling. The PSO as an optimization tool provides a population-based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in a multidimensional search space [15].

This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

$$v(k+1) = w.v(k) + c_1.rand(P_{best} - x(k)) + c_2.rand(G_{best} - x(k)) \quad (18)$$

Using the above equation, a certain velocity, which gradually gets close to $P_{best}$ and $G_{best}$ can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$x(k+1) = x(k) + v(k+1) \qquad for \quad k = 1,2,...n \quad (19)$$

Where *x(k)* is current searching point ,*x(k+1)* is modified searching point ,*v(k)* is current velocity ,*v(k+1)* is modified velocity . $P_{best}$ is the best solution observed by current particle and $G_{best}$ is the best solution of all particles, w is an inertia weight, $c_1$ and $c_2$ are two positive constants, rand is a random generated number with a range of [0,1] [16]. The proposed control using PSO is shown by Figure 11.

The PSO algorithm is now utilized in order to get the online determination of the weighting factors α and β given in (15-17) (factors α and β gains for the tracking error between reference and measured torque, stator flux respectively) of the predictive direct torque and flux control based on absolute errors :

$$\alpha|\Delta T_e(k+1)| + \beta|\Delta\psi_S(k+1)|\ ) \quad (20)$$

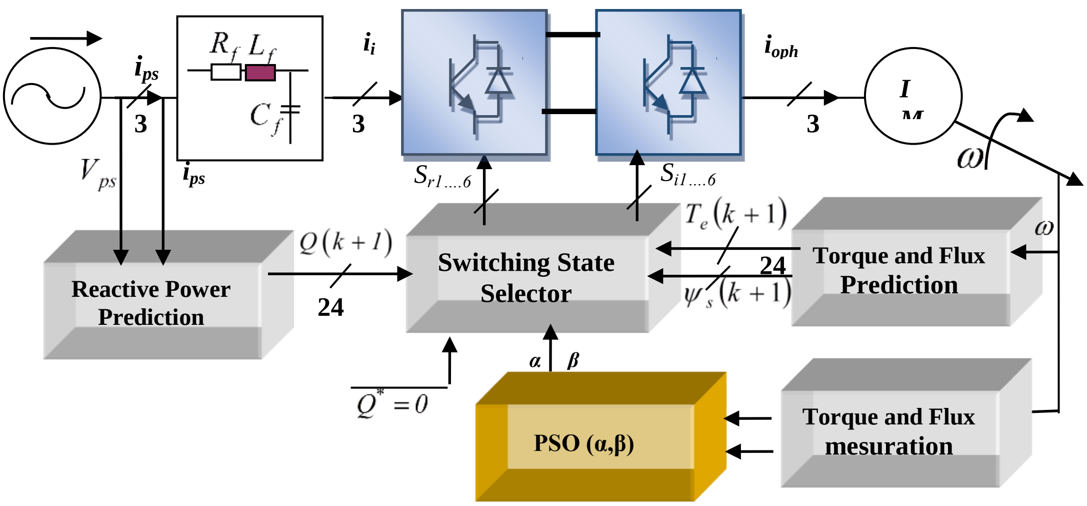



Figure 11. Scheme of predictive torque and flux control using PSO

The PSO based approach to find the global maximum value of objective function as shown in Figure 12 and Figure 13. The strategy succeeded in maintaining voltage balance in the DC link as shown in Figure 14.

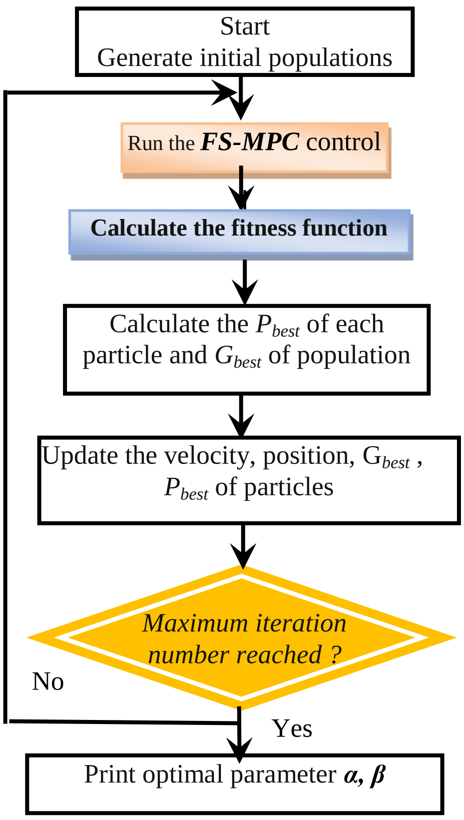



Figure 12. Flowchart of the PSO- αβ control

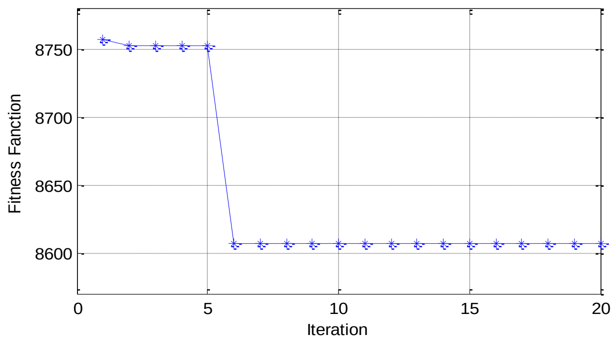



Figure 13. The fitness function variation

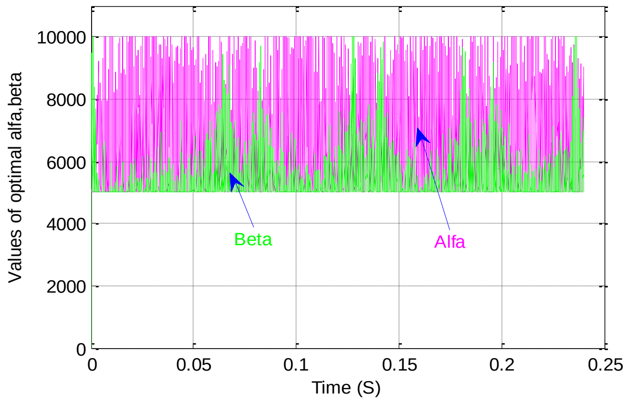



Figure 14. Variation of α and β during simulation

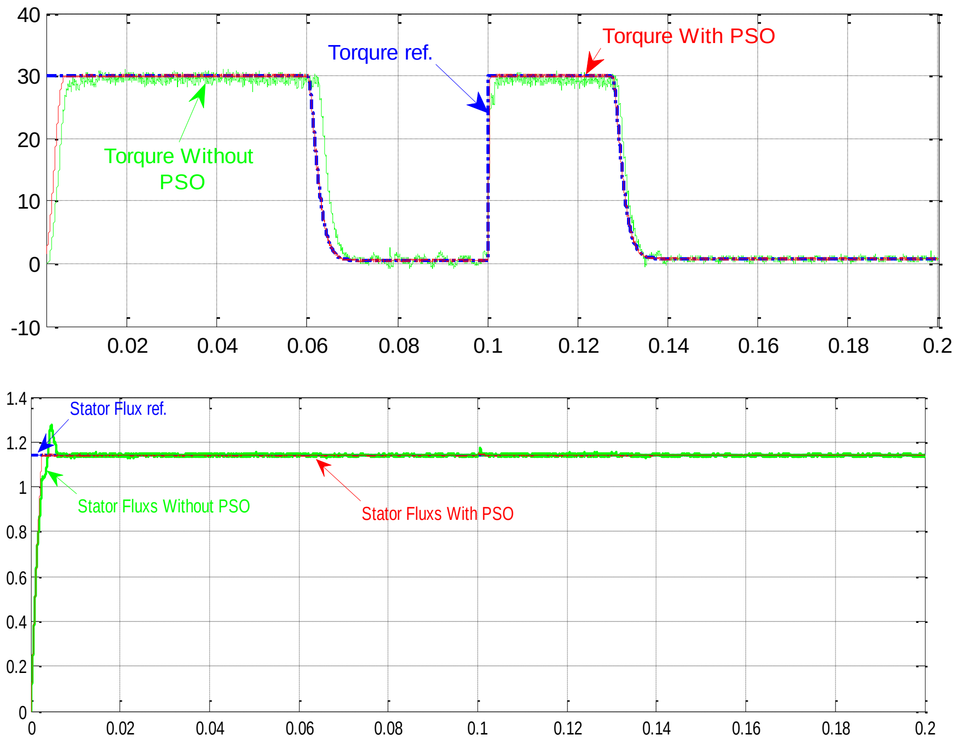



Figure 15 (a, b). Simulation results of torque and Stator flux with and without PSO

A comparison done here with the results obtained from predictive torque and flux control method with reactive power minimization. The results of the comparison are that the torque and stator flux ripple is reduced considerably with the help of PSO as shown in Figure 15 (a,b). In addition, the startup is reduced and good tracking property in case of ‘‘with PSO’’ compared with a case of ‘‘without PSO’’.

## 6. CONCLUSION

A very simple and effective predictive torque and flux control method with reactive power minimization applied in an indirect converter has been presented in this work. The strategy offers the possibility to control both the torque and flux, to maintain unity power factor. A particle swarm optimization with predictive direct torque and flux control is proposed. The PSO algorithm returns the values of weighting factor. The control scheme uses a discrete model of the converter, induction machine and to obtain the best-suited converter switching state considering the torque, flux and reactive power error. By the evaluation of the 24 possible combinations of the topology for indirect converter without DC-link energy storage. The ideal minimum of the cost function is zero and represents the perfect regulation of the controlled variables, this is unity power factor and a given machine torque and flux. With DC-link energy, storage converter, the quality function to be minimized for the inverter is the error between reference and actual torque, flux and of the rectifier control is to regulate the DC-link voltage while having sinusoidal input currents in phase with their respective supply line voltages. The quality function to be minimized for the rectifier is the error between the zero and actual reactive power for unity power fact.

Indeed, simulation results show an accurate tracking for torque and flux variations where it was observed that when the drive system works under unbalanced conditions, a supplement ripples and oscillations on torque, flux, whereas, when the PSO algorithm was used and returned the optimal values of weighting factor, better results have been obtained in term of low torque and flux ripples and oscillations.

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