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# Experiment based comparative analysis of stator current controllers using predictive current control and proportional integral control for induction motors

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**ABSTRACT**

The stator current control loop plays an important role in ensuring the quality of electric drives interm of producing fast and adequate required torque. When the current controller provides ideal responses, speed control design subsequently is in charge of improving the system performances. Classical PID control is commonly used in current loop design, this paper presents the comparative analysis of current stator controller using proportional integral control and predictive current control (PCC) in field-oriented control-based induction motor drives, with rigidly coupled loads. The experimental results show system responses with PID and PCC. Informative experiment-based analysis provides primary guidance in selection between the two controls.



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## 1. INTRODUCTION

Due to the importance of electrical drive system in modern industrial applications, numerous studies have been conducted on the structure of the system. One of the most common frequency control methods for the induction motor drive proposed is scalar control, which is considered as inadequate in high quality motion applications [1]. Proven to possess more advantages than scalar control method for speed control of the induction motor, vector control methods find their place in various motion control systems [2, 3].

Well-known for its simplicity, direct torque control (DTC) regulates motor flux and torque in a direct way. However, DTC control possesses a major difficulty during low speed ranges. Many researches are conducted to provide a solution to the existing issues of the coupling between flux and torque forming components of the stator current vector [4]. The field-oriented control (FOC) scheme is developed based on successfully controlling the decoupled current components using closed-loop control. The FOC structure for the induction motor includes stator currents loop with fast time constants and outer loops such as speed and position control loops with greater time constant [3, 5]. With the FOC control structure, many linear or nonlinear controls are implemented [6-13]. The classical PI controller can only be effective around the operating point, when operating in a wide range the system performance can be degraded [14]. Nonlinear methods, with more computational requirements, exhibit its ability in a wide operating range. Several control schemes used in FOC based induction motor drives can be found in [3, 5].

Recently, the application of model predictive control (MPC) in electric drives attracts many researchers. The basic principle of MPC is to calculate the optimum values for actuating variables based on mathematical model of the system, the historic control actions and the optimization of cost function over a receding prediction horizon. MPC has many advantages such as intuitive concept and simple implementation [15]. MPC can be classified into two categories: continuous MPC and finite set control MPC (FSC-MPC). Continuous MPC requires complex modulations and its algorithm is complicated. Because of its easy realization of nonlinear control and constraints (e.g., over current protection, switching loss minimization, etc.) inclusion capability, FSC-MPC attracts research attentions and efforts. FSC-MPC does not need any continuous actuating variable or modulator. In FSC-MPC, the model of inverter is directly taken into consideration in the controller [16]. Every feasible switching vector is considered in the calculation of the cost function. The one minimizing the cost function is selected as the optimal output. FSC-MPC (for simplicity, hereafter referred to as MPC) has been successfully used in almost all kinds of applications in power electronics, including DC-DC, DC-AC, AC-DC and AC-AC converters [17-19]. As for electrical drives systems, MPC has been deeply investigated for AC machines [20-22]. MPC can also be used for sensorless drive systems with achieved good performances [23, 24]. Different prediction horizon based MPC methods have been considered. With longer prediction steps, better performances are expected to be obtained. However, problems of time consuming calculation must be solved.

This paper presents the design, analysis and comparison of the stator currents responses, by using PI controller (PI-FOC) and predictive current control (PCC-FOC). When the stator current regulator via the cost function in PCC-FOC, we can achieve objective features in the closed loop responses [3, 5]. When implementing the stator voltage control satisfies the requirement of “fast-accuracy-decoupling” properties in current response, the induction motor can be considered as fed by a controllable current source inverter, which leads to order reduction of induction motor drive system from 4th to 2nd order [25]. Thus, it is essential to produce fast, accurate current (torque) with small ripple and overshoot.

## 2. MODEL OF INDUCTION MOTOR AND MODELS OF VOLTAGE SOURCE INVERTER

### 2.1. Mathematic model of induction machine

The induction motor model in the $d-q$ reference frame was obtained [14]:

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{1}{T_\sigma^{'}} i_{sd} + \omega_s i_{sq} + \dfrac{k_r}{r_\sigma T_\sigma^{'} T_r}\psi_{rd} + \dfrac{1}{r_\sigma T_\sigma^{'}} u_{sd} \\ \dfrac{di_{sq}}{dt} = -\omega_s i_{sd} - \dfrac{1}{T_\sigma^{'}} i_{sq} - \dfrac{k_r}{r_\sigma T_{\sigma r}^{'}}\omega\psi_{rd} + \dfrac{1}{r_\sigma T_\sigma^{'}} u_{sq} \\ \dfrac{d\psi_{rd}}{dt} = \dfrac{L_m}{T_r} i_{sd} - \dfrac{1}{T_r}\psi_{rd} \\ \dfrac{d\omega}{dt} = \dfrac{3}{2}\dfrac{z_p^2 L_m}{L_r J}\psi_{rd} i_{sq} - \dfrac{z_p T_L}{J} \end{cases} \tag{1}$$

With parameters used in the model shown as:

$\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$ : leakage factor; $T_s = \dfrac{L_s}{R_s}$ : stator time constant

$T_r = \dfrac{L_r}{R_r}$ : rotor time constant

Coefficients: $k_r = \dfrac{L_m}{L_r}$; $r_\sigma = R_s + R_r k_r^2$; $T_\sigma^{'} = \dfrac{\sigma L_\sigma}{r_\sigma}$

$\omega_s = \omega + \dfrac{L_m}{T_r}\dfrac{i_{sd}}{\psi_{rd}}$ : slip estimation

Where: $\omega$ : Mechanical rotor speed
$z_p$ : Number of pole pairs
$J$ : Torque of inertia
$T_L$ : Torque load
$\psi_{rd}$ : Rotor flux
$L_m, L_r, L_s$ : Mutual, rotor, stator inductance

### 2.2. Mathematic model of inverter

A two-level three-phase voltage source inverter (VSI) serves as the power converter in this work. Its topology and all feasible voltage vectors are displayed in Figure 1. Switching state **S** is in the form of a vector sum:

$$S_i, \bar{S}_i = 1,0 \mathbf{S} = \frac{2}{3}(S_a + \mathbf{a}S_b + \mathbf{a}^2 S_c) \tag{2}$$

in which $a = e^{j2\pi 3}$, shows the on, off states of the upper, lower switches of lag *i*, with $i = a,b,c$. The output voltage vector ***v*** is of the same amplitude of DC link voltage and calculated from switching state ***S*** as:

$$\mathbf{v} = V_{dc}\mathbf{S} \tag{3}$$

## 3. EVALUATION OF PI CURRENT CONTROLLER IN FOC STRUCTURE

PI control for stator current in IM is well established, hence PI control in $d$ and $q$ stator currents are in the following forms without further explanation [14, 23]:

$$\begin{aligned} u_{sd} &= K_c^d (i_{sd}^* - i_{sd}) + (\frac{K_c^d}{T_I^d}\int (i_{sd}^* - i_{sd}))dt - \frac{k_r}{T_r}\psi_{rd} - T_\sigma^{'} r_\sigma \omega_s i_{sq} \\ u_{sq} &= K_c^q (i_{sq}^* - i_{sq}) + (\frac{K_c^q}{T_I^q}\int (i_{sq}^* - i_{sq}))dt + r_\sigma T_\sigma^{'} \omega_s i_{sd} + k_r \omega \psi_{rd} \end{aligned} \tag{4}$$

From equation of PI stator current controllers using FOC of an induction machine with PI controller as shown in Figure 1.

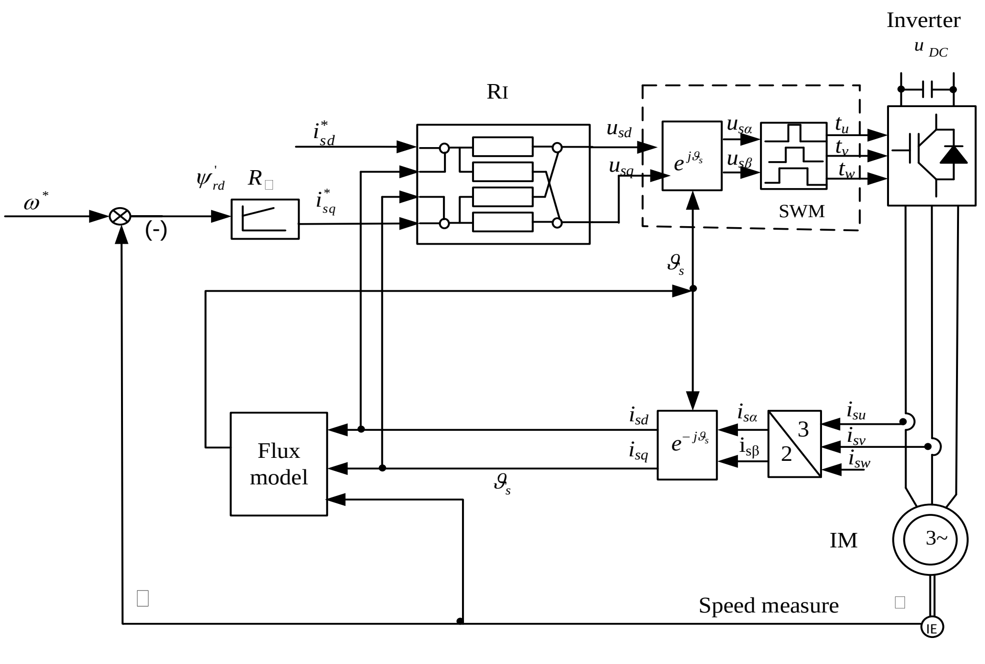



Figure 1. Block structure of the PI stator current controllers

## 4. EVALUATION OF PREDICTIVE CURRENT CONTROLLER (PCC) IN FOC STRUCTURE

The model predictive control structure for FOC is based on a flux rotor calculation of the IM fed by a two-level voltage source inverter. Assuming that the measured signals such as speed motor ω, stator currents $i_{s\alpha}, i_{s\beta}$ are available. Based on previous studies [14, 16], the estimated stator currents are expressed by equation:

$$i_{s\alpha}(k+1)=\phi_{11}i_{s\alpha}(k)+h_{11}u_{s\alpha}(k)+\phi_{13}\psi'_{r\alpha}(k)+\phi_{14}\psi'_{r\beta}(k)$$
$$i_{s\beta}(k+1)=\phi_{11}i_{s\beta}(k)+h_{11}u_{s\beta}(k)+\phi_{13}\psi'_{r\beta}(k)-\phi_{14}\psi'_{r\alpha}(k) \quad (5)$$

where: $\phi_{11}=1-\frac{T}{\sigma}(\frac{1}{T_s}+\frac{1-\sigma}{T_r});\phi_{13}=\frac{1-\sigma}{\sigma}\frac{T}{T_r};\phi_{14}=\frac{1-\sigma}{\sigma}\omega T;h_{11}=\frac{T}{\sigma L_s}$

The motor flux can be estimated as:

$$\psi'_{r\alpha}=\frac{T}{T_r}i_{s\alpha}(k-1)+(1-\frac{T}{T_r})\psi'_{r\beta}(k-1)-\omega T\psi'_{r\beta}(k-1) \quad (6)$$

$$\psi'_{r\beta}=\frac{T}{T_r}i_{s\beta}(k-1)+(1-\frac{T}{T_r})\psi'_{r\alpha}(k-1)-\omega T\psi'_{r\beta}(k-1) \quad (7)$$

According to (6), (7) flux is calculated through the measured $i_\beta(k+1)i_\alpha,i_\beta\psi'_{r\alpha},\psi'_{r\beta}u_\alpha(k),u_\beta(k)i_\alpha(k),i_\beta(k)$ value of the stator current and speed motor ω and flux rotor from in the previous step. With the flux calculated according to (6), (7) line stator model is shown to be the stator model (5) in step (k+1) with the input control voltage and current of stator measured at time *k*.

The model predictive control method calculates cost functions for all sectors, since it is the method that obtains the reference voltage by selecting the minimum value, it has the advantage of selecting the most optimal voltage vector which include several limitations and nonlinear characteristics. When actualizing the basic MPC algorithm of the three-level inverter, the voltage vector is selected by calculating 8 cost functions. However, since the selected reference voltage vector is applied for one period, it has a drawback of having severely large ripples of torque and flux compare to the calculation. The predictive control scheme and algorithm for induction motor control are presented in Figure 2 respectively. The cost function in the predictive control of IM with delay compensation is presented as:

$$g=\left|\mathrm{i}^*[k+1]-\mathrm{i}[k+1]\right| \quad (8)$$

where: $\left|\mathrm{i}^*[k+1];\mathrm{i}[k+1]\right|$ is the value of the applied current vector and the current vector on the load at the time (k+1) predicted by (5). With a small sampling period, we can approximate the amount of $i^*[k+1]\approx i[k]$. From there, rewrite (8) the cost function in the *αβ* coordinate system:

$$g=\left|i^*_\alpha(k)-i_\alpha(k+1)\right|+\left|i^*_\beta(k)-i_\beta(k+1)\right| \quad (9)$$

where: $i_\alpha(k+1)$ and are the real of the predicted stator current phasor; $i^*_\alpha(k)$, $i^*_\beta(k)$ are the respective desired parts of the current space phasor reference. With the two-level inverter diagram we have eight switching states of three valve branches, meaning that in each cycle of time sample T we perform eight calculations and the target function (9), will find one the eight most appropriate states to make the rectifier open and close. The algorithm performs the selection of the voltage vector for less than algorithm 1. Predicted stator current controller combined flux estimation model and PCC model fed by a two level voltage source inverter as shown in Figure 2.

Algorithm 1. Voltage vector selection algorithm

Input $i_\alpha,i^*_\alpha,i^*_\beta,i_\beta,\psi'_{r\alpha},\psi'_{r\beta}$
**for** i=1:8
Calculation of **v** by (3)
Calculation of $i_{s\alpha}(k+1),i_{s\beta}(k+1)$ by (5)
Calculation of $g$ by (9)
Min of $g$
Out put $S_a$, $S_b$, $S_c$
**end for**
0: Apply **V** to electric machine through VSI at next control cycle.

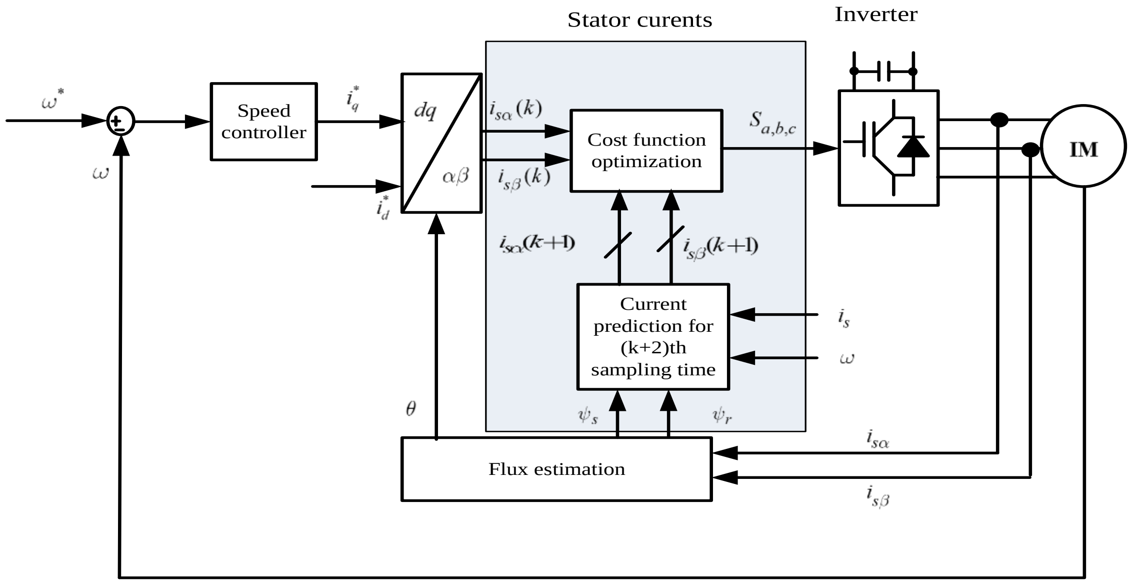



Figure 2. Block structure of the stator current controllers with predictive current controller

## 5. EXPERIMENTAL RESULTS

The stator current controllers using PI-FOC and PCC-FOC with speed controller is PI controller, where the rotor flux $\psi_{rd}$ is established and has a constant value in sections 3 and 4 verified through experimental. Experiments are conducted on an IM machine with parameters in Table 1. Test bench is shown in Figure 3. The stator current controllers using PI-FOC and PCC-FOC with speed controller are PI controller, where the rotor flux $\psi_{rd}$ is established and has a constant value in sections 3 and 4 verified through experimental. Model parameters are given in the Table 1.

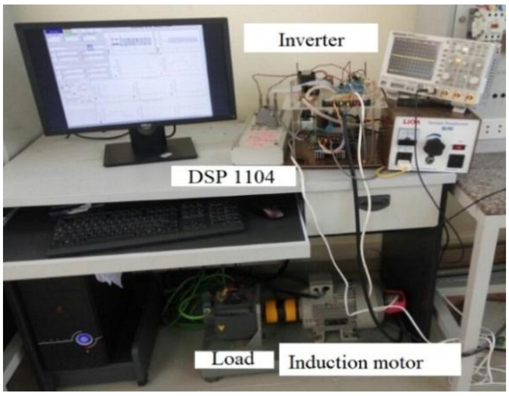
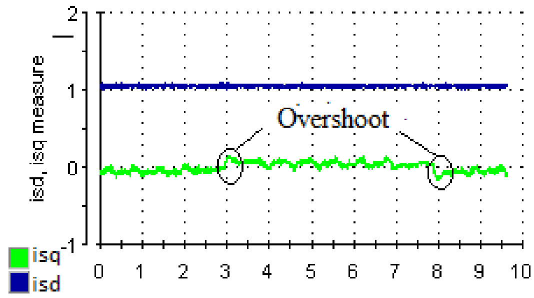



Figure 3. Photo of experimental setup

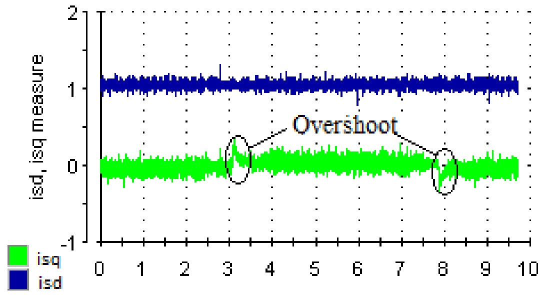
Table 1. Model parameters of induction motor

| Parameters | Nomenclature | Value |
|---|---|---|
| Rated power | $P_{nom}$ | 1.5 kW |
| Rated Torque | $n_{nom}$ | 2880 vg/ph |
| Rated phase current | $I_{nom}$ | 4.7 $A_{RMS}$ |
| Number of pole pairs | $z_p$ | 1 |
| Rotor resistance | $R_r$ | 0.42 Ω |
| Stator resistance | $R_s$ | 0.37 Ω |
| Rotor inductance | $L_r$ | 34.25 mH |
| Stator inductance | $L_s$ | 34.41 mH |
| Mutual inductance | $L_m$ | 33.1 mH |
| Torque of inertia | J | 0.001 $kgm^2$ |
| Frequency modulation | $f_{pwm}$ | 5 kHz |

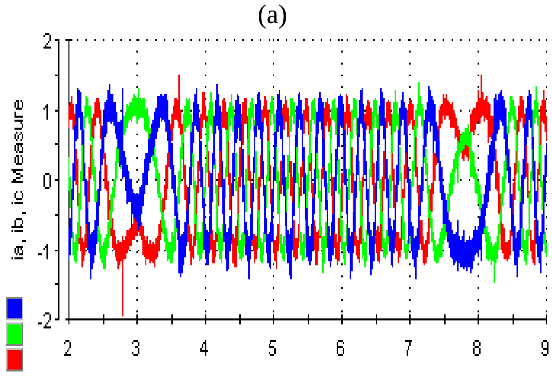
Experimental procedure: at t=0 (s) create magnetic current; t=4 (s) speed up to 20 rad/s; t=8.8 (s) speed down to -20 rad/s. In the test, a sudden torque with rated value of 1.5 Nm is applied on the motor shaft. The results of the simulation of stator current controllers using PI-FOC and PCC-FOC are shown in Figure 4.



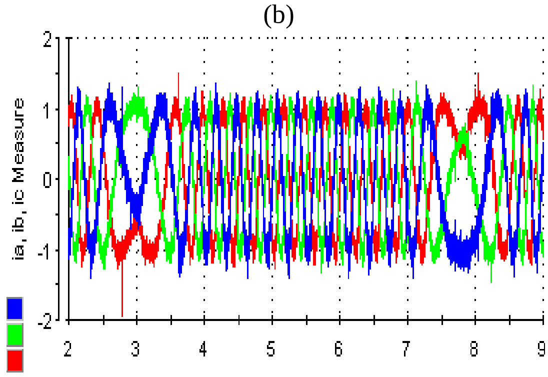

(a)



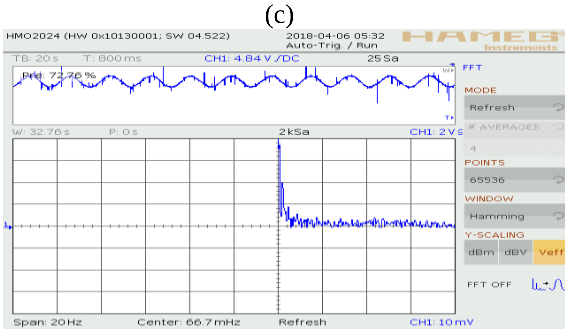

(b)



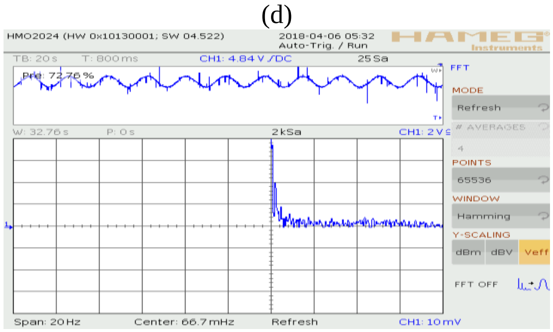

(c)




(d)




(e)




(f)

Figure 4. Stator current responses, (a) Stator current response using PCC-FOC, (b) Stator current response using PI-FOC, (c) 3 phase stator current response PCC-FOC, (d) 3 phase stator current response PI-FOC, (e) Total harmonic distortion (THD%) PCC-FOC, (f) Total harmonic distortion (THD%) PI-FOC

From the result in Figure 4, the dynamic response evaluation stator current of controllers shows the setting time and overshoot and total hamonic distortion THD% for both controllers are given in the Figure 5. The experimental results show its high performance. PCC reduces the system cost, shortens its response time and improves. Moreover, there is hardly any work for the cost function the general dynamics. It can be observed from numerical and experimental results that all two current controls have steady speed control performance, low torque ripples and fast response. However, PI current control than those of the PCC control.

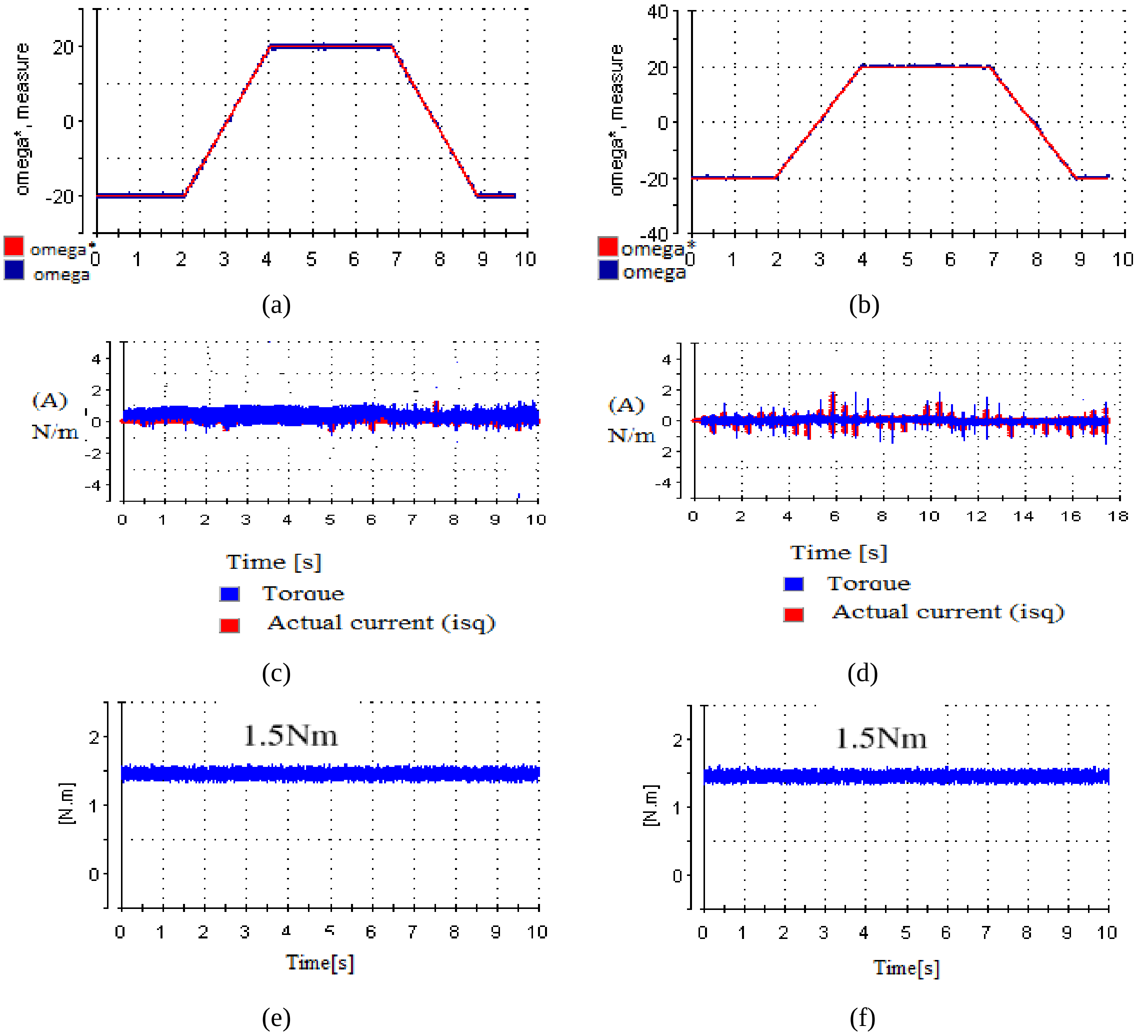



Figure 5. Torque and speed responses, (a) Speed response PCC-FOC, (b) Speed response PI-FOC, (c) Torque response with no load PCC-FOC, (d) Torque response with no load PI-FOC, (e) Torque response with load PCC-FOC, (f) Torque response with load PI-FOC

## 6. CONCLUSION

In this paper, predictive current control of an induction machine fed by a two-level voltage source inverter model is proposed and the mathematical model of the predictive current is derived. By applying 8 switching states of voltage vectors, the one that produces the predictive current, closest to the reference current, is selected. The model is verified in experimental, and the results demonstrate the speed and electromagnetic torque of the motor have a good dynamic response for a wide speed range at both no load and loaded conditions. However, the ripple of electromagnetic torque is significant high. Further improvement needs to be done to reduce the ripple. And to promote all abilities to predict many states, the use of multi-level inverter migh be the proper choice and the should be further studied. On the other hand, the stator current control PI-FOC showed the stability of the settling.

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