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# Induction Motor Position Controller Based on Rotational Motion Equations

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**ABSTRACT**

This paper presents a proposed position controller for a vector controlled induction motor. The position controller design depends on the rotational motion equations and a classical speed controller (CSC) performance. The CSC is designed to have the ability to track variable reference inputs and to provide a predefined system performance. Standard position controller in industry is presented to analyze its performance and its drawbacks. Then the proposed position controller is designed, based on the well defined rotational motion equations. The proposed position controller and the CSC are applied to control the position and speed of the vector controlled induction motor with different ratings. Simulation results at different operating conditions are presented to evaluate the proposed controllers' performance. The results show that the CSC can drive the motor with a predefined speed performance and can track a variable reference speed with an approximately zero steady state error. The results also show that the proposed position controller has the ability to effect high-precision positioning in a limited time and to track a variable reference position with a zero steady state error.

**Keywords:** Variable speed drive, Position and speed controllers, Induction motor

## 1. Introduction

Motion control can be defined as the application of high performance servo drives to rotational or translational control of torque, speed, and position [1]. At present, many systems are available for such purposes including DC motor drives, variable-reluctance stepper drives, and brushless DC motor drives. However, the greatest progress has been made in recent years by the induction motor servo drives. The field-oriented controlled induction motors provide a very wide speed range and a mechanically robust and relatively low-cost motion control option [2]. Various control methods have been proposed [3-6]. Applying those design methods, control objectives can be achieved, and parameters uncertainties can be effectively compensated.

Speed and position control problems are among the common control problems arising in industrial controls and many disciplines of engineering. Many theoretical and experimental treatments for these problems have been proposed and can be found in the literature [7-9]. The standard approach in industry is to use a PI speed loop and a proportional position loop with a speed command separately fed, via what is generally described as, a "speed feed-forward" path [10].

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This present paper introduces a modified version of the CSC which was introduced in [11]. Then a position controller is designed based on the proposed speed controller performance and the rotational motion equations. The controllers' parameters can be calculated to professionally satisfy a predefined system performance at all the operating conditions.

## 2. The Classical Speed Controller (CSC)

In [11] the following equation was suggested to represent the CSC output assuming a constant speed command (step function command):
The Controller output = integration of

$$[k_1[(\omega_m^* - \omega_m) - k_2(\omega_m - \omega_{mo})]] \quad (1)$$

Where $\omega_m$ and $\omega_{mo}$ are the instant motor speed sampled value and its previous sampled value respectively, $k_1$ and $k_2$ are constants, and $\omega_m^*$ is the command (reference) speed.

The CSC is applied to control the speed of a field oriented controlled induction motor. The induction motor drive system block diagram, including the speed controller and the position controller, are shown in Fig.1. In [11] the following equations were used to calculate the CSC parameters:

$$k_2 = 2\sqrt{\frac{J\eta}{k_1}} \quad (2)$$

$$\mathrm{M_{dip}} = \frac{T_L}{k_1 * k_2} \quad \text{rad/sec} \quad (3)$$

$\mathrm{M_{dip}}$ is the maximum dip in motor speed at a load torque change from no load to full load. $J$ is the motor inertia and $\eta$ is a damping factor (all definitions can be obtained in [11]). Based on equations (2) and (3) the CSC parameters can be calculated to provide a motor speed with a certain damped response and a full load torque rejection with a predefined maximum dip.

## 3. The CSC Application to 50hp Induction Motor

The CSC is applied to control the speed of a 50hp induction motor. The motor parameters are listed in Table1 [12]. The controller parameters $k_1$ and $k_2$ can be calculated based on equations (2) and (3) to provide a critically damping speed response with a maximum full load disturbance dip of 1rad/sec as follows:

$$k_1 * k_2 = \frac{T_L}{M_{dip}} = \frac{200}{1} = 200 \quad \text{Nm/(rad/sec)}$$

$$k_2 = \frac{4 * J}{200} = \frac{4 * 1.662}{200} = 0.03324$$

$$k_1 = \frac{200}{k_2} = \frac{200}{0.03324} = 6017 \quad \text{Nm/(rad/sec)}$$

Fig.2 shows the performance of the drive system to a 160rad/sec step increase of speed reference and a 200Nm full load torque is applied to the motor at time=1.5sec, followed by 160rad/sec step decrease of speed reference at t=2.5sec. Fig.2 shows that the CSC satisfies the required performance; fast and critically damped speed response with a maximum speed dip less than 1rad/sec for a full load torque disturbance. To clearly show the dip in speed, a figure zoom is done as shown in the right part of Fig. 2.

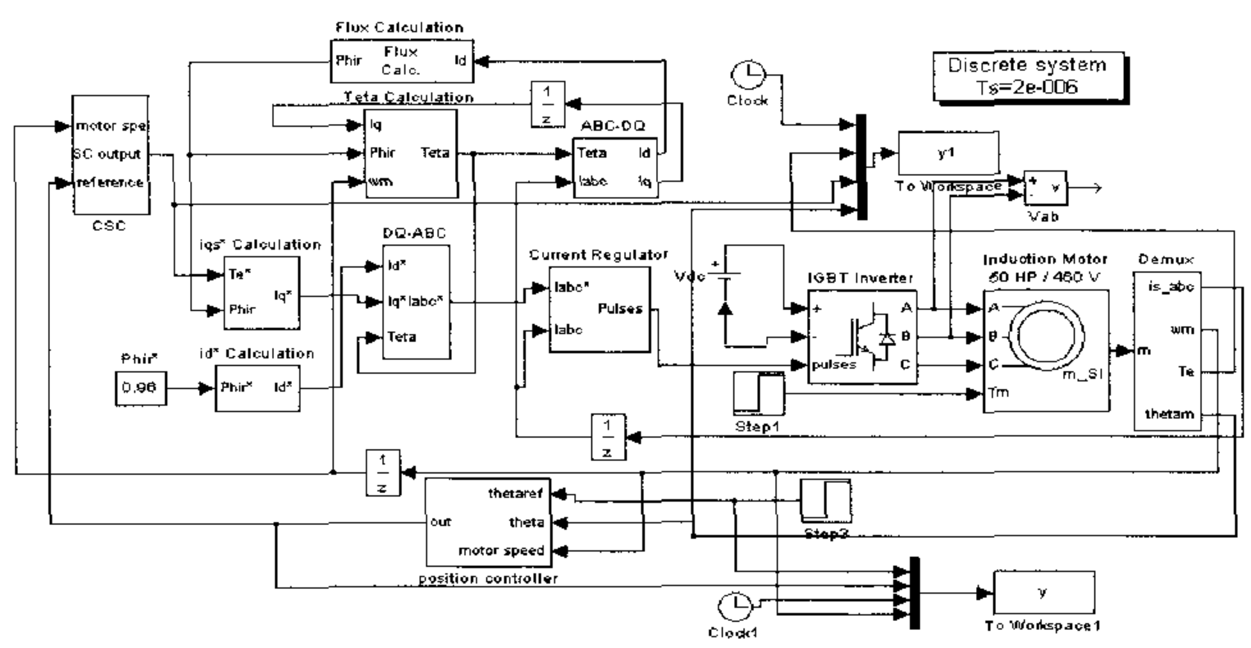


Fig. 1 MATLAB/SIMULINK model of the induction motor drive system with CSC and the proposed position controller

Fig.3 shows the performance of the CSC to track a sine wave speed reference at no load condition. The left part of Fig. 3 shows the reference speed and the actual speed. They seem to be identical. But as shown in the right part of Fig.3, there is a steady state speed error between the reference speed and the actual speed. This error is a result of assuming a constant reference in equation (1). To eliminate this error in speed, a modified version of the CSC is suggested.

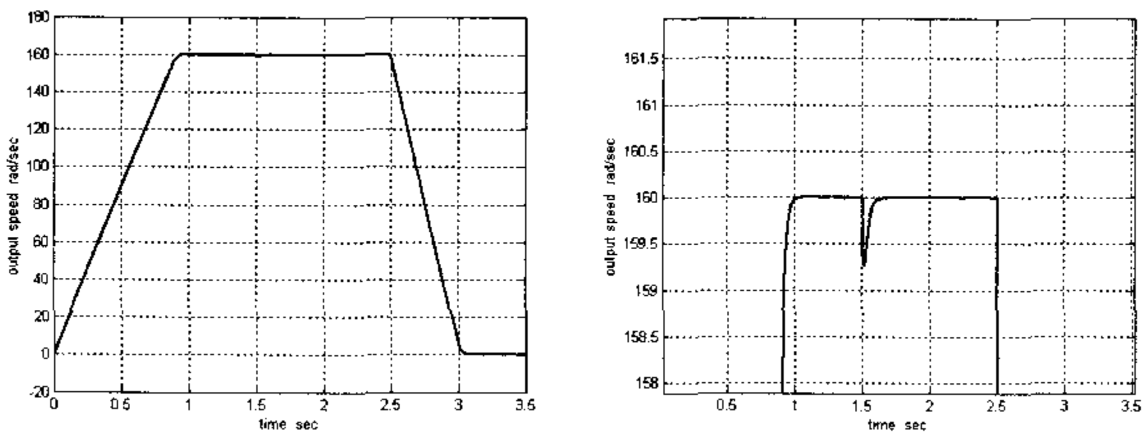

Fig. 2 the CSC performance to provide a critically damped speed response and a maximum full load disturbance dip of 1rad/sec.

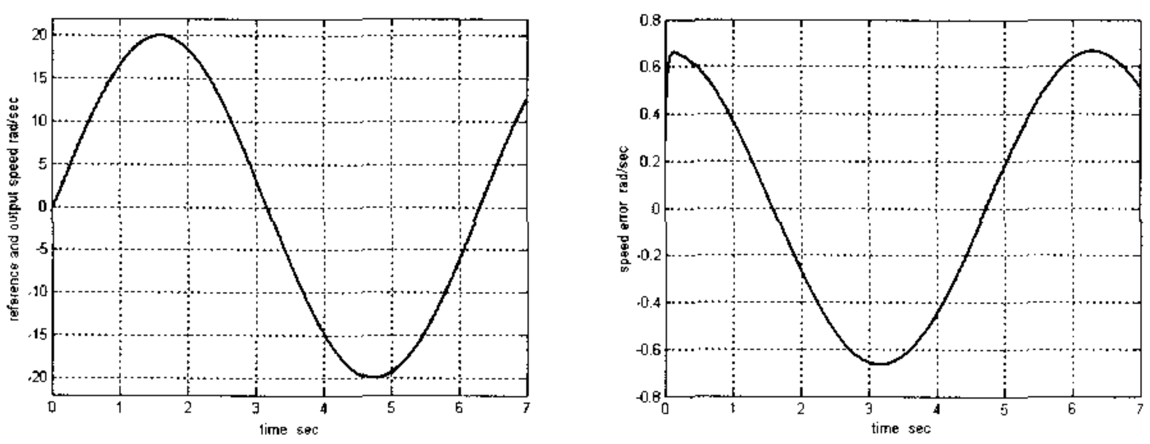

Fig. 3 the performance of the CSC (assuming a constant reference input) to track a sine wave speed reference at no load condition (output speed and its error)

The suggested output equation of the modified version of the CSC is as follows:

CSC output = integration of

$$[k_1[(\omega_m^* - \omega_m) + k_2(\omega_m^* - \omega_{mo}^*) - k_2(\omega_m - \omega_{mo})]] \quad (4)$$

This equation assumes a general reference speed input. Where $\omega_m^*$ and $\omega_{mo}^*$ are the instant value of the sampled reference speed and its previous value respectively. Equation (4) can be represented in the z-domain using MATLAB/SIMULINK program as shown in Fig.4

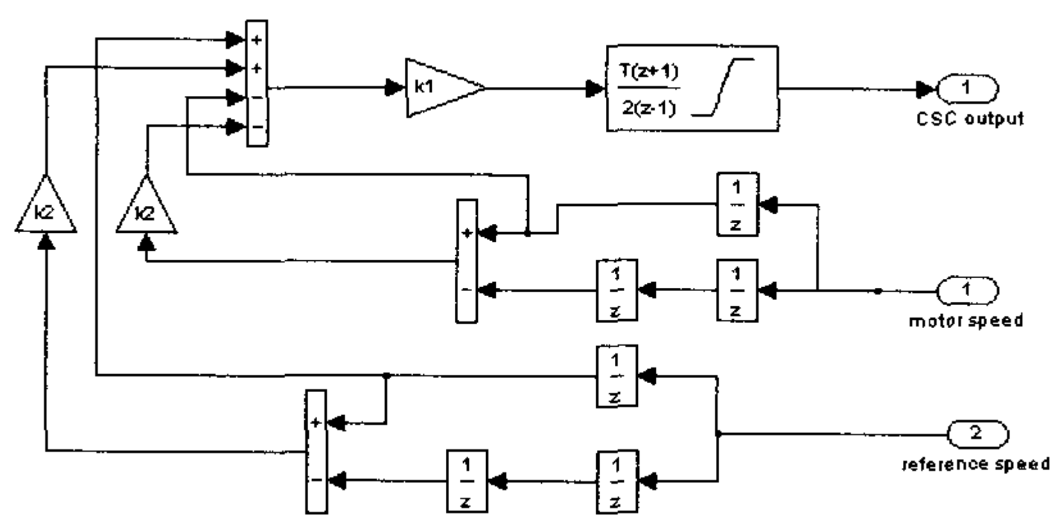


Fig. 4 the CSC model in z-domain assuming a general reference input

Using equation (4), Fig.5 shows the performance of the CSC to track a sine wave speed reference at no load and full load conditions at different frequencies (Fig.5a and Fig.5b). The left part of Fig.5 shows the motor speed at no load and full load conditions. The right part of Fig. 5 shows the steady state error in the two cases. The error is approximately equals to zero and there is no difference between the performance in no-load and full load conditions.

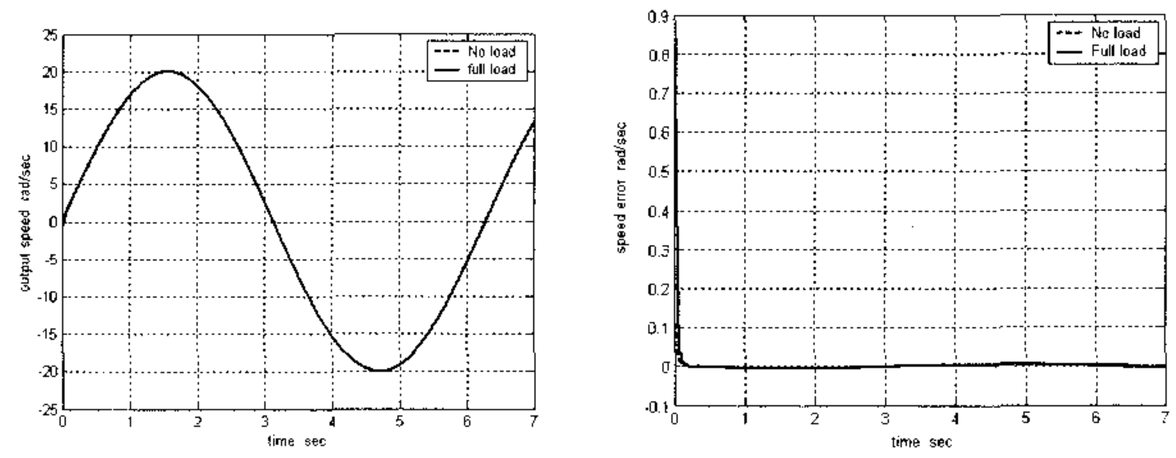

Fig. 5a the performance of the CSC to track a sine wave speed reference at no load and full load conditions (the output speed and its error)

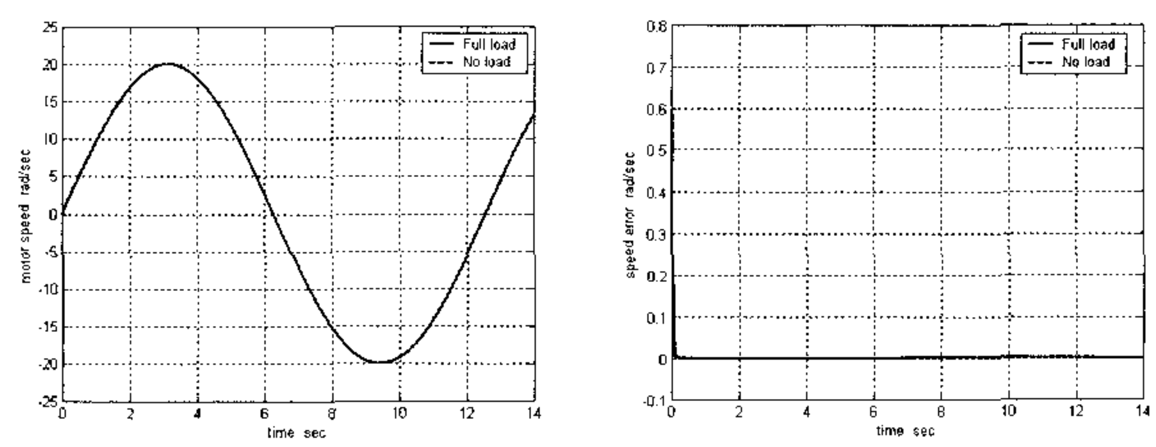

Fig. 5b the performance of the CSC to track a sine wave speed reference at no load and full load conditions (at different reference frequency)

## 4. Standard Position Controller

Standard approach in industry is to use a proportional position loop with a speed command separately fed via what is generally described as a "speed feed-forward" path[10]. This approach can be represented by the following equation:

Standard position controller output =

$$kp(\theta^* - \theta) + \frac{d\theta^*}{dt} \quad (5)$$

The first term of equation (5) represents a classical proportional controller, where $kp$ is the proportional gain and $(\theta^* - \theta)$ is the position error. The second term of (5) is very important to cancel any steady state position error while applying a variable position command (such as sine wave function). Equation (5) represents the reference speed of the speed controller. It can be simulated using MATLAB/SIMULINK program as shown in Fig.6. T is the sampling time.

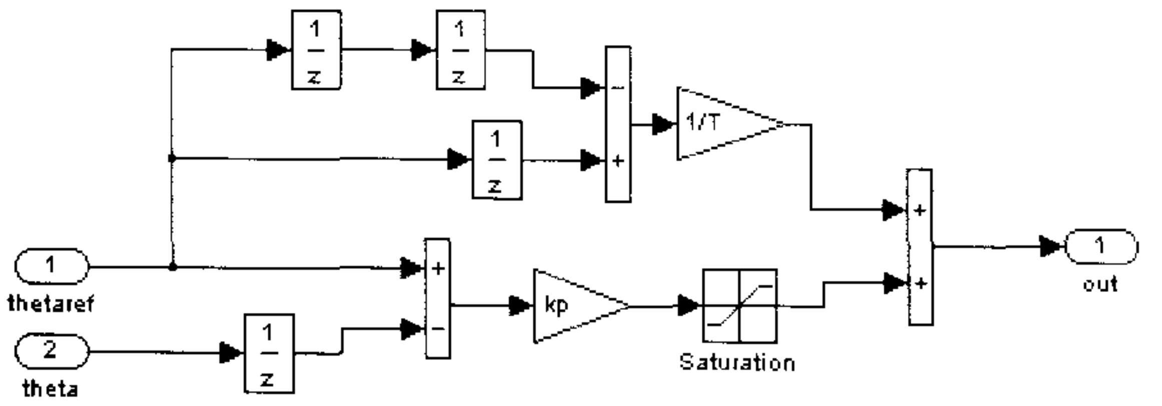


Fig. 6 the z-domain model of the standard position controller

Using this position controller (with $kp$ = 6) along with the CSC, the performance is shown in Fig.7 at different step position commands (10rad and 30rad step increase) and different system inertias (J=J and J=3J). It is clear from Fig. 7 that the controller performance deteriorates as the reference step increases and as the system inertia increases. To eliminate the overshoot in the position response, $kp$ should be as small as possible. In this case the system will be very slow.

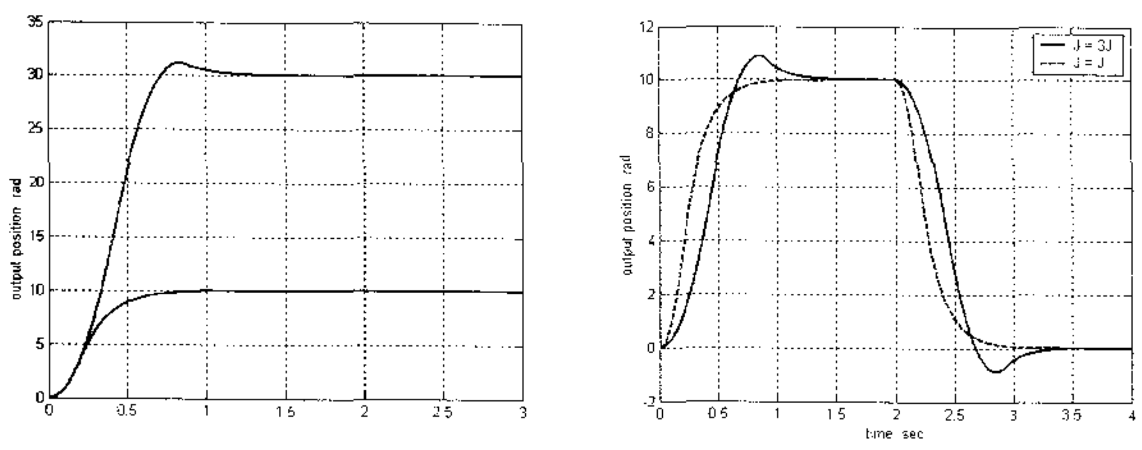

Fig. 7 the performance of the standard position controller at different step position commands and different system inertias

## 5. The Proposed Position Controller

Equation (5) shows that the reference speed is proportional to the position error which contrasts the well defined rotational motion equation below:

$$\omega^2 = \omega_o^2 + 2a(\theta^* - \theta) \tag{6}$$

Equation (6) shows that the position error $(\theta^* - \theta)$ is proportional to the square of the final speed $\omega$ at a constant acceleration $a$ and a zero initial speed $\omega_o$. Thus, the following equation is suggested to represent the proposed position controller:

The proposed position controller output

$$= \sqrt{2a(\theta^* - \theta)} + \frac{d(\theta^* - \theta)}{dt} + \frac{d\theta^*}{dt} \tag{7}$$

The first term of equation (7) represents the main part of the reference speed. The second term is a damping factor which represents the change of error. The third term is used to cancel any steady state position error while applying a variable position command.

Equation (7) can be re-written as follows:

The proposed position controller output

$$= \sqrt{|\theta^* - \theta|}\, sign(\theta^* - \theta)\sqrt{2a} - \frac{d\theta}{dt} + 2\frac{d\theta^*}{dt} \tag{8}$$

Using MATLAB/SIMULINK program, equation (8) can be simulated as shown in Fig.8, where $k$ is the square root of $(2a)$.

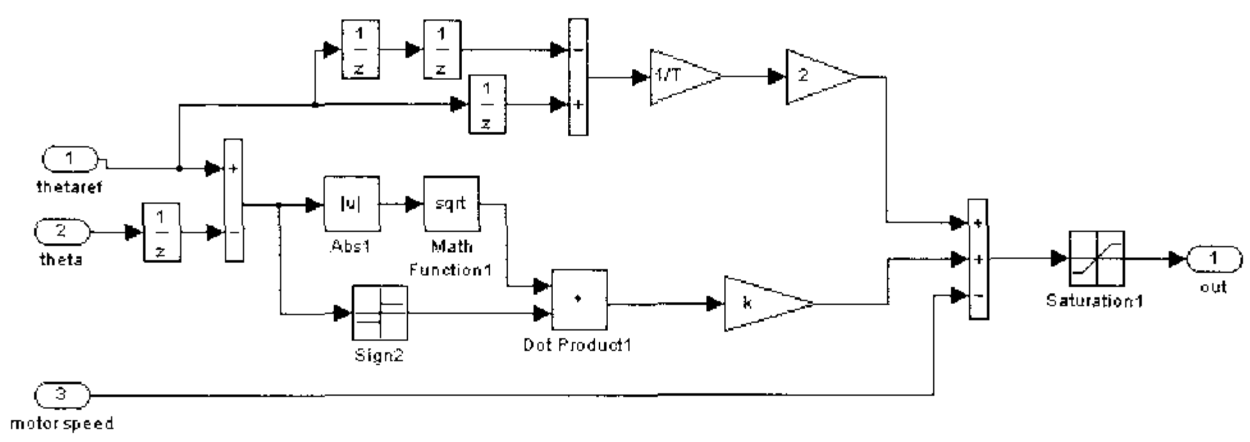


Fig. 8 the proposed position controller model

### 5.1 Calculation of the system acceleration ($a$)

From the system mechanical equation, the acceleration depends on the output of the speed controller, the load torque, the system inertia, and the friction coefficient. The following equation can be used to obtain the system acceleration:

$$a = \frac{T_e^* - T_L - B\omega_m}{J} \tag{9}$$

It is proposed to use the maximum system acceleration in equation(9). The maximum acceleration can be obtained by setting $T_e^*$ to $T_{\max}$ (maximum allowable torque) and $T_L$ to zero and $\omega_m$ to rated speed. In this case, for our system:

$$a = \frac{300 - 0.1 * 183}{1.662} = 169.5 \text{ rad/sec}^2$$

The parameter $k$ in Fig.8 can be calculated as follows:

$$k = (2a)^{0.5} = (2 * 169.5)^{0.5} = 18.4$$

The performance of the proposed position controller with this calculated acceleration is shown in Fig.9, where different reference position step changes are applied (10rad and 30rad). A 10rad reference position step increase is also applied then decreased again at different system inertias (J=J and J=3J). It is clear that as the step reference increases or is at different system inertias, the proposed position controller has the same performance. There is no overshoot at any case; the settling time is also less for all of the cases compared with the results shown in Fig.7 for the standard position controller. Furthermore, Fig.10 shows the performance of the proposed position controller to track a sine wave input at no load condition. The left part shows the motor output position and the right part shows the error between the command position and the actual position. As shown in the right part, the steady state error is approximately equal to zero.

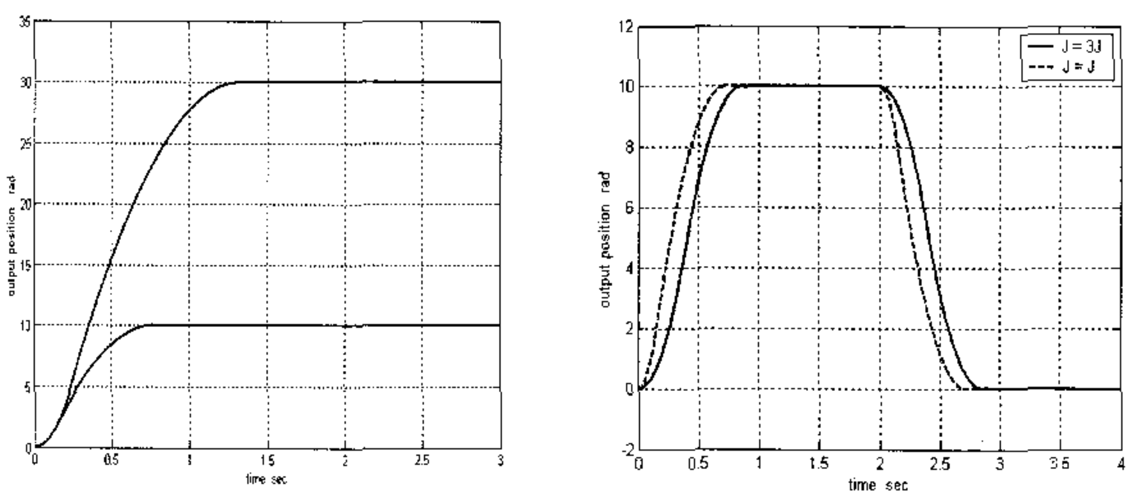

Fig. 9 the proposed position controller performance at different position commands and different system inertias

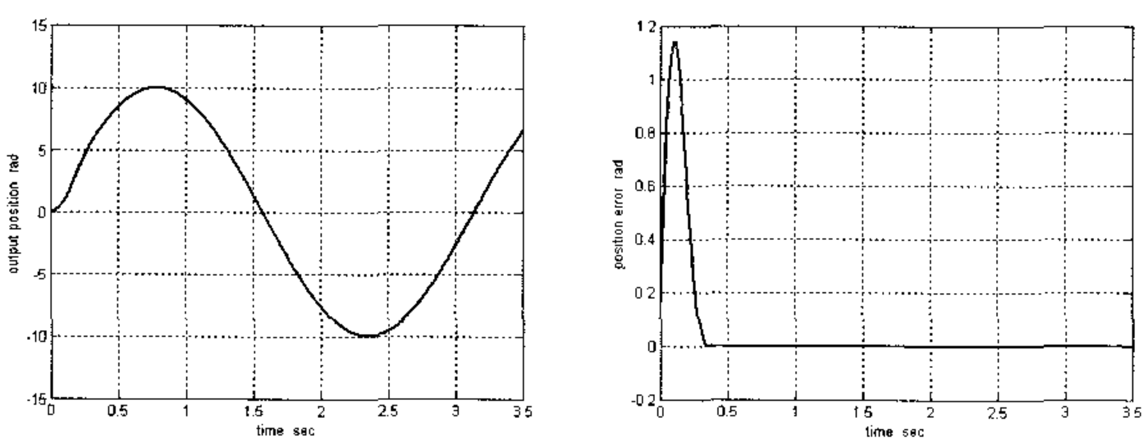

Fig. 10 the position controller performance to track a sine wave reference input (the output position and its error)

The motor output position and speed are shown in Fig.11 at a 400rad reference position step increase. As shown in the right part of Fig.11, the motor is running with a constant acceleration followed by a constant speed then with a constant deceleration to achieve the required position. The motor torque in this case is shown in Fig.12.

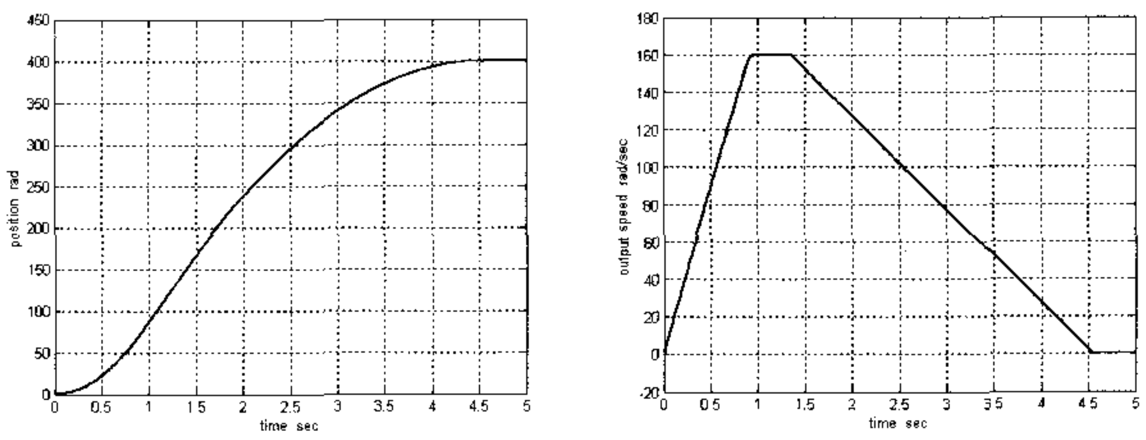

Fig. 11 The motor output position and speed at a 400rad step position command

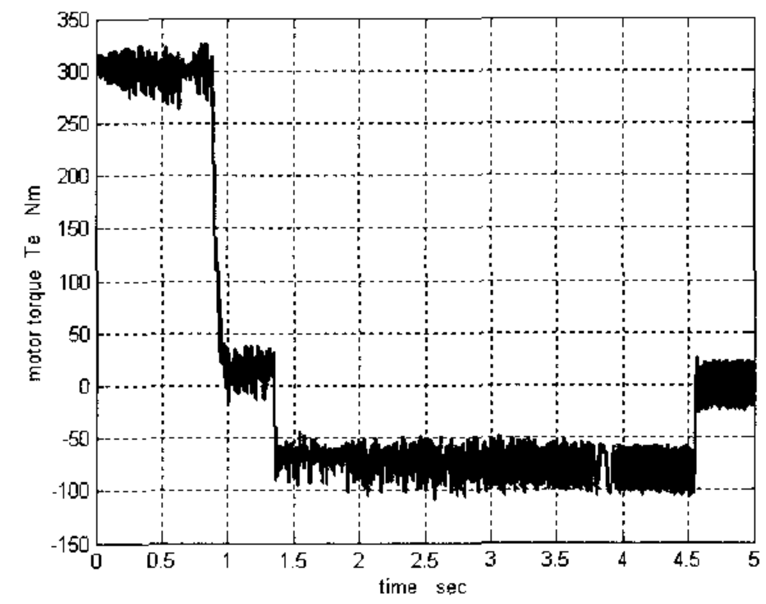

Fig. 12 The motor output torque at a 400rad step position command

## 6. Application to 0.43kw Induction Motor

This present paper introduces position and speed controllers for induction motors. The controllers' parameters can be calculated to professionally satisfy a predefined system performance at all the operating conditions. To ensure this outcome, the controllers are used to control the position and speed of a 0.43kW induction motor with a critically damped speed response and a maximum speed dip less than 2rad/sec for a full load torque disturbance. The motor parameters are listed in table1 [13].

Table 1 Specifications of induction motors

| | | |
|---|---|---|
| rated power | 0.43 KW | 50 hp |
| rated voltage | 460V | 460V |
| rated speed | 175 rad/sec | 183rad/sec |
| rated torque | 2.5 Nm | 200Nm |
| rated frequency | 60 Hz | 60Hz |
| pole pairs | 2 | 2 |

| | | |
|---|---|---|
| system inertia | 0.0008 kg m2 | 1.662kgm$^2$ |
| stator resistance | 27.55 Ω | 0.037 Ω |
| rotor resistance | 21.4 Ω | 0.228 Ω |
| stator and rotor inductances | 0.055 H | 0.8 mH |
| magnetizing inductance | 0.822 H | 34.7mH |
| friction factor | 0 | 0.1Nmsec |

The parameters of the CSC and the proposed position controllers can be calculated as follows:

$$k_1 * k_2 = \frac{T_L}{M_{dip}} = \frac{2.5}{2} = 1.25 \text{ Nm/(rad/sec)}$$

$$k_2 = \frac{4 * J}{1.25} = \frac{4 * 0.0008}{1.25} = 0.00256$$

$$k_1 = \frac{1.25}{k_2} = \frac{1.25}{0.00256} = 488.3 \text{ Nm/(rad/sec)}$$

$$a = \frac{3.75 - 0 * 175}{0.0008} = 4687.5 \text{ rad/sec}^2$$

$$k = (2a)^{0.5} = (2 * 4687.5)^{0.5} = 96.8$$

The performance of the proposed controllers with these calculated parameters are shown in Fig.13. Fig.13a shows the performance of the drive system to a 100rad/sec step increase of speed reference and a 2.5Nm full load torque is applied to the motor at time=0.3sec, followed by a 100rad/sec step decrease of speed reference at t=0.8sec. To clearly show the dip in speed, a figure zoom is done as shown in the right part of Fig. 13a. Fig.13b shows the performance to track a sine wave speed reference at no load condition. The left part shows the motor output speed and the right part shows the error between the reference speed and the actual speed. In Fig. 13c, a 10rad reference position step increase is applied then decreased again at different system inertias (J=J and J=4J).

## 7. Conclusions

This paper presents a proposed position controller for a vector controlled induction motor. The position controller design depends on the rotational motion equations and a classical speed controller performance. The CSC is designed to have the ability to track variable reference inputs and to provide a predefined system performance. A standard position controller in industry is presented to analyze its performance and its drawbacks. Then, the proposed position controller is designed based on the well defined rotational motion equations. The models of the CSC, standard position controller, and the proposed position controller are simulated by the MATLAB/SIMULINK program. The proposed position controller and the CSC are applied to control the position and speed of vector controlled induction motor with different ratings; 50hp and 0.43kW. Simulation results at different operating conditions are presented to evaluate the performance of the proposed controllers. The results show that the CSC can drive the motor with a predefined speed performance and can track a variable reference speed input with an approximately zero steady state error. Moreover, the results show that the proposed position controller has the ability to effect high-precision positioning in a limited time and to track a variable reference position input with a zero steady state error.

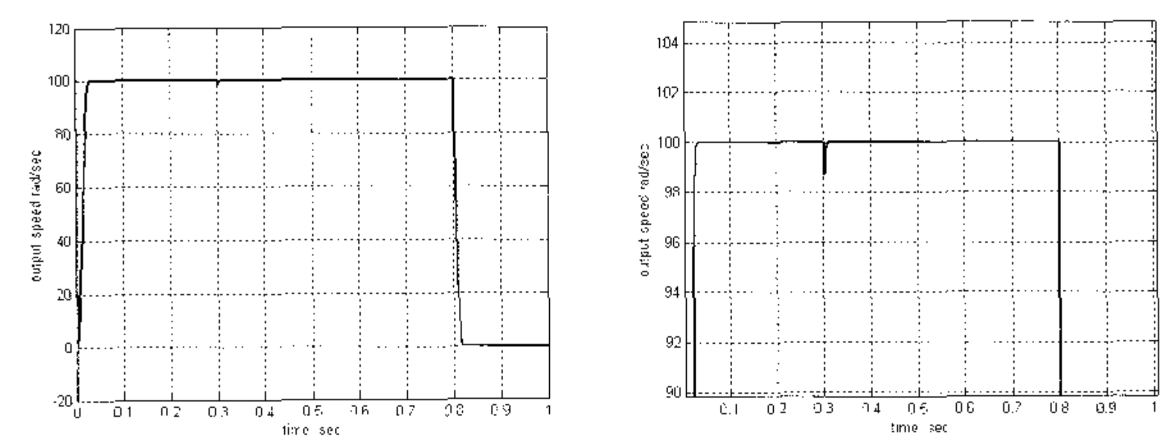

Fig. 13a step speed commands and full load disturbance (without and with zooming)

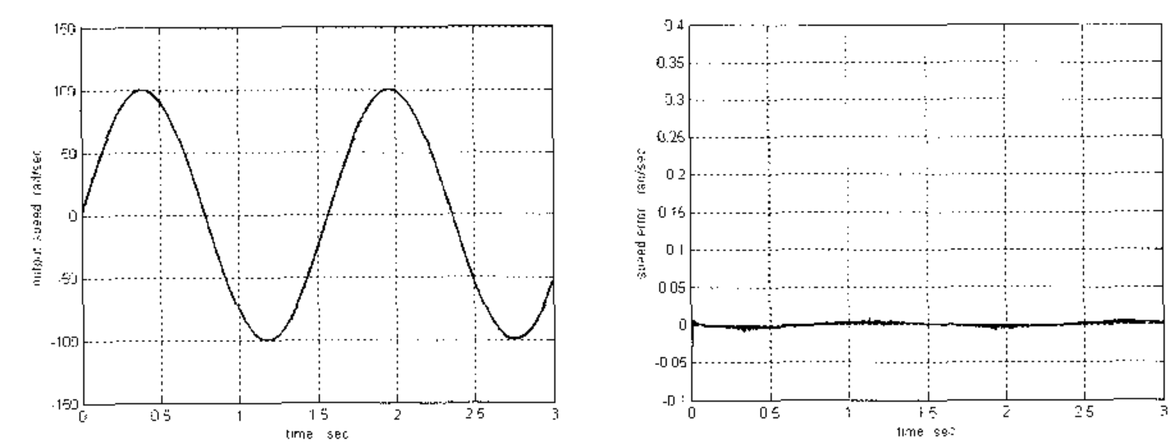

Fig. 13b tracking a sine wave speed reference (the output speed and its error)

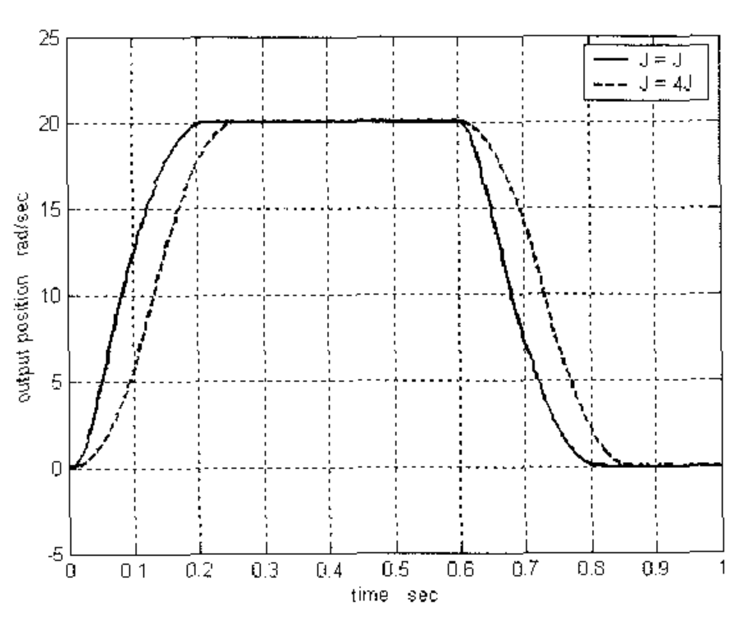

Fig. 13c the output position for different inertias

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