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Enhanced Performance of Three-Phase Squirrel-Cage Induction Machine Drive System using Model-predictive-controller in MATLAB/SIMULINK environment

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Abstract

From decades, the three-phase squirrel-cage induction motors are widely being used as industrial drives as they are self-starting, rugged, reliable, and economical, but its precise torque control is still a challenge. Therefore, this work presents a systematic design procedure to develop the novel control strategy, *i.e.*, the model predictive controller for an induction machine drive system using an input-output linearized model of this machine. The results of the proposed scheme are compared with the conventional Proportional Integral (P-I) controller-based system, showing the superior performance of the model predictive controller using MATLAB/SIMULINK environment. The parameters of P-I controller have been calculated using Zeigler Nicholas (ZN) method.

Keywords: Induction Motor, Model Predictive Control, Proportional Integral Controller.

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Introduction

An electrical drive system constitutes an electric motor driving a mechanical load, directly or through a gearbox, and the associated control equipment such as power converters, switches, relays, sensors, and microprocessors. Occasionally, in drive systems with difficult start-up due to a high torque and/or inertia of the load, simple means for reducing the starting current are employed. In applications where the speed, position, or torque must be controlled, Adjustable Speed Drives (ASDs) with dc motors are still common. ASDs with induction motors have increasing popularity in industrial practice due to their ruggedness, self-starting nature, reliability and low cost.[1,2] However, its control is difficult. The progress in control means and methods for these motors, particularly spectacular in the last decade, has resulted in the development of several classes of ac ASDs having a clear competitive edge over dc drives [1]. Variable speed control of induction motor evolved from scalar control method like *V/f* control to more sophisticated and efficient vector-control methods.[3]

Methods like field-oriented control (*FOC*) and direct torque control (*DTC*) are now very mature and widely used in many industrial applications. *FOC* method is based on generating the torque and flux references using classical proportional integral (*P-I*) controller.[4,5] The field orientation theory is utilized to generate the required reference voltage to be applied. On the other hand, *DTC* works directly on the torque and flux. Based on the sign torque and flux errors and a lookup table, the suitable voltage vector is selected and applied. For controlling the electromagnetic torque of three phase asynchronous motor, there are many control techniques, one of which is the classical control technique which uses proportional plus integral controllers (*P-I*). But, the tuning of *P-I* controller is not an easy task. Also, the *P-I* controller has some disadvantages such as high starting overshoot, sensitivity to controller gains and sluggish response to sudden disturbances. There are also other control techniques such as H∞ control, robust control, sliding mode control and the MPC control, out of which, except MPC, all

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other techniques are difficult to implement. So, the *MPC* is proposed as torque controller for the induction motor drives to overcome the disadvantages of the *P-I* controller.

Model predictive control (*MPC*) techniques are characterized by their simple and intuitive concept. They are suitable for multivariable systems. Moreover, the constraints and nonlinearity could be easily handled but it needs formidable calculations. Therefore, they have been used in application characterized by long time constant like chemical and some process control-based industries.[6] Recently, the development of mathematical models of electrical machines and power converters along with the recent powerful microprocessors pave the way for implementations of various *MPC* methods in power electronics. More recently, the concept of *MPC* have been heavily utilized for power converters of different topologies.[7]

In this work, a model predictive controller is designed for the precise electromagnetic torque control of a three phase squirrel cage induction motor in MATLAB/SIMULINK environment. The transient torque characteristics of this three phase squirrel cage induction motor showing the dynamic variation of the electromagnetic torque in reference to the reference load torque with the MPC and PI controllers are obtained using MATLAB/SIMULINK and the results of which are discussed in the later sections.

System Description

The dynamic simulation is one of the quintessential steps in the validation of the design process of the motor-drive systems, eliminating the inadvertent design mistakes and the resulting errors in the prototype construction and testing and hence necessitates for the dynamic model of the induction machine. In this section, the dynamic modelling of the Induction motor, along with the modelling of the PI and the MPC controller is presented.

Dynamic Modelling of the Induction motor

The dynamic model (*d, q* model)[2,8] of a 3-phase induction motor in synchronously rotating reference in matrix form is given by

$$[v^\gamma]=[Z^\gamma][i^\gamma] \tag{1}$$

where $[v^\gamma]$ and $[i^\gamma]$ represents the '4 × 1' column matrices of voltage and current and are given by

$$[v^\gamma] = [\, v_{qs}\; v_{ds}\; v_{qr}\; v_{dr}]^T \tag{2}$$

$$[i^\gamma] = [\, i_{qs}\; i_{ds}\; i_{qr}\; i_{dr}]^T \tag{3}$$

and $[Z^\gamma]$ is '4 × 4' impedance matrix and is given by

$$\begin{bmatrix} R_s+sL_s & \omega_e L_s & sL_m & \omega_e L_m \\ -\omega_e L_s & R_s+sL_s & -\omega_e L_m & sL_m \\ sL_m & (\omega_e-\omega_r)L_m & R_r+sL_r & (\omega_e-\omega_r)L_r \\ -(\omega_e-\omega_r)L_m & sL_m & -(\omega_e-\omega_r)L_r & R_r+sL_r \end{bmatrix} \tag{4}$$

where, s = Laplacian operator, v_{qs} = quadrature axis stator voltage, v_{ds} = direct axis stator voltage, v_{qr} = quadrature axis rotor voltage, v_{dr} = direct axis rotor voltage, R_s = stator winding resistance, L_s = stator winding leakage inductance, L_m = magnetizing inductance, R_r = rotor winding resistance referred to the stator, L_r = rotor winding leakage inductance refereed to the stator, ω_e = synchronous speed with respect to d^s-q^s axes,and ω_r = rotor speed.

Now, since in a squirrel cage induction motor, the rotor bars are permanently short circuited by end rings. Therefore, for a single fed squirrel cage asynchronous motor, $v_{qr} = v_{dr}$ = 0. Thus (3) becomes,

$$[v^\gamma] = [\, v_{qs}\; v_{ds}\; 0\; 0]^T \tag{5}$$

The equation of electromagnetic torque produced in the induction motor is given as

$$T_e = \frac{3}{2}\frac{P}{2}L_m\,(i_{qs}i_{dr} - i_{ds}i_{qr}) \tag{6}$$

The speed ω_r in (4) cannot normally be treated as a constant. It is related to the torques as

$$T_e = T_L + J\frac{d\omega_r}{dt} \tag{7}$$

Equations (1), (6) and (7) give the complete model of the electro-mechanical dynamics of the induction machine in synchronous frame. The composite system is of the fifth order and non-linearity of the model is evident.

In order to evaluate the transfer function of the induction machine, it can be linearized on a small-signal perturbation basis at a steady-state operating point. The advantage of such a transfer function model is that the stability analysis of the drive system at the quiescent point becomes possible using classical control theory, such as Bode, Nyquist, or Root-Locus technique [8]. Since the system is non-linear, the poles, zeros, and gain of the transfer function will vary as the steady-state operating point shifts. The close loop control system with *MPC* can thus be designed with controller parameters such that at the worst operating point, the system is adequately stable and the satisfactory performances are achieved.

As seen from the formidable set of equations, i.e., (1), (6) and (7), the dynamic model of the induction motor can be assembled in the matrix form and on applying small signal perturbation about a steady-state operating point [8], we get a matrix equation of the following format

$$[A + \delta A] = [B + \delta B]\,[C + \delta C] \tag{8}$$

where,

$$[A+\delta A] = \begin{bmatrix} v_{qso} + \delta v_{qs} \\ v_{dso} + \delta v_{ds} \\ 0 \\ 0 \\ T_{Lo} + \delta T_L \end{bmatrix}, \tag{9}$$

$$[B+\delta B]=[B_{11}B_{12}B_{13}B_{14}B_{15}]_{5\times 5} \quad (10)$$

where,

$$B_{11}=\begin{bmatrix} R_s+sL_s \\ -(\omega_{eo}+\delta\omega_e)L_s \\ SL_m \\ -(\omega_e-\omega_r)L_m \\ \frac{3}{2}\left(\frac{P}{2}\right)L_m(i_{dro}+\delta i_{dr}) \end{bmatrix}, \quad (11)$$

$$B_{12}=\begin{bmatrix} (\omega_{eo}+\delta\omega_e)L_s \\ R_s+sL_s \\ sL_m \\ -(\omega_e-\omega_r)L_m \\ \frac{3}{2}\left(\frac{P}{2}\right)L_m(i_{dro}+\delta i_{dr}) \end{bmatrix}, \quad (12)$$

$$B_{13}=\begin{bmatrix} sL_m \\ -(\omega_{eo}+\delta\omega_e)L_m \\ R_r+sL_r \\ -(\omega_e-\omega_r)L_r \\ 0 \end{bmatrix}, \quad (13)$$

$$B_{14}=\begin{bmatrix} (\omega_{eo}+\delta\omega_e)L_m \\ sL_m \\ (\omega_e-\omega_r)L_r \\ R_r+sL_r \\ 0 \end{bmatrix}, \text{ and} \quad (14)$$

$$B_{15}=\begin{bmatrix} 0 \\ 0 \\ -L_m(i_{dso}+\delta i_{ds})-L_r(i_{dro}+\delta i_{dr} \\ L_m(i_{dso}+\delta i_{ds})+L_r(i_{dro}+\delta i_{dr}) \\ -\frac{2}{P}sJ \end{bmatrix} \quad (15)$$

, and

$$[C+\delta C]=\begin{bmatrix} i_{qso}+\delta i_{qs} \\ i_{dso}+\delta i_{ds} \\ i_{qro}+\delta i_{qr} \\ i_{dro}+\delta i_{dr} \\ \omega_{ro}+\delta\omega_r \end{bmatrix}. \quad (16)$$

where T_L = Load torque disturbance considered as input signal and the parameters $v_{qso}, v_{dso}, v_{qro}, v_{dro}, T_{Lo}, \omega_{eo}, i_{qso}, i_{dso}, i_{qro}, i_{dro}$, and ω_{ro} represents the steady-state operating point and can be evaluated by solving the equations with all the time derivatives (terms with *s*) equated to zero. Equation (8) can be linearized by neglecting the δ^2 or higher order terms and ousting out steady-state terms, which yields the small-signal linear state-space equation in the form:

$$\dot{X}=AX+BU \quad (17)$$

where,

$$X=[\Delta i_{qs}\ \Delta i_{ds}\ \Delta i_{qr}\ \Delta i_{dr}\ \Delta\omega_r]^T \quad (18)$$

$$U=[\Delta V_s\ 0\ 0\ 0\ \Delta\omega_e\ \Delta T_L]^T \quad (19)$$

The developed torque is obtained from the currents by the equation

$$\Delta T_e=\frac{3P}{4}L_m[(i_{dro}\Delta i_{qs}+i_{qso}\Delta i_{dr})-(i_{dso}\Delta i_{qr}+i_{qro}\Delta i_{ds})] \quad (20)$$

Referring (7), let us assume that for a given drive system, the induction motor is subjected to time varying load torque, which in turn will change the speed of the rotor accordingly, but after the sudden change, the machine's speed must settle down to a constant value, failing to which the machine will be subjected to varying acceleration or deceleration leading to instability.

In order for the rotor to attain a constant speed after being subjected to a sudden change in load torque, the electromagnetic torque must be equal to the reference torque, i.e., $T_e = T_L$. Substituting in (7), we get

$$\frac{2}{P}J\frac{d\omega_r}{dt}=0 \quad (21)$$

which yields ω_r = constant. Thus, by making $T_e = T_L$, the induction motor will attain a constant speed. This can be obtained with a controller, *P-I* as well as with *MPC* controller.

Design of P-I Controller

The block diagram representation[9] of the P-I controller is as shown in Fig. 1.

The actuating signal, *a*(*t*), for a PI controller is expressed as

$$a(t)=K_p e(t)+K_i\int e(t)\,dt \quad (22)$$

Taking Laplace Transform of (22), we get

$$A(s)=K_pE(s)+\frac{1}{s}K_iE(s) \quad (23)$$

Rearranging (23), we get

$$\frac{A(s)}{E(s)}=K_p+\frac{1}{s}K_i \quad (24)$$

The transfer function of the P.I. controller is thus given by,

$$H(s)=\frac{A(s)}{E(s)} \quad (25)$$

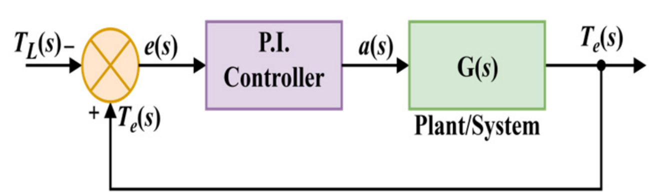

Fig. 1: Block diagram of a classical feedback control loop (PI control)

From (24) and (25), we have

$$H(s) = K_p + \frac{1}{s} K_i \qquad (26)$$

The value of K_p (proportional gain) and K_i (integral gain) is determined with the help of Ziegler Nichols (ZN) Method. The Zeigler Nichols[10] continuous cycling method or ultimate gain method is one of the best-known closed loop tuning strategies and was developed in 1942, and for the motor under consideration, the value of the gains K_p and K_i has been obtained using the ZN method with the help of MATLAB/SIMULINK which are as follows:

$$K_p = 0.9489 \text{ and } K_i = 400 \qquad (27)$$

MPC Modelling

MPC is an advanced control method, which explicitly uses the model to predict the future performance of the system. Taking into account this prediction, the MPC determines an optimal output *'w'* by solving a constrained optimization problem. It is one of the few control methods that directly considers constraints.[6]

Often, the cost function is formulated in such a way that the system output *'y'* tracks a given reference *'r'* for a prediction horizon N_2.

Assuming an arbitrary system [6],

$$x(\beta+1) = f(x(\beta), w(\beta)), \qquad (28)$$

$$y(\beta) = h(x(\beta)) \qquad (29)$$

MPC minimizes a user-defined cost function 'Λ'

$$\min_w \Lambda(x(\beta), w(\cdot)) \qquad (30)$$

Now, the cost function Λ(*x*(β), *w*(·)) is defined as

$$\Lambda = \sum_{k=N_1}^{N_2} \|r(\beta+i/\beta) - y(\beta+i/\beta)\| \qquad (31)$$

Substituting (31) in (30), we get

$$\min_w \sum_{k=N_1}^{N_2} \|r(\beta+i/\beta) - y(\beta+i/\beta)\| \qquad (32)$$

such that

$$w_{lb} \le w(\beta+j \mid \beta) \le w_{ub}$$
$$y_{lb} \le y(\beta+i \mid \beta) \le y_{ub}$$

$$\forall\, i \in \{N_1, \ldots\ldots, N_2\} \text{ and } j \in \{0, \ldots\ldots, N_u\}.$$

This formulation uses an arbitrary norm ||·||. We refer to the predicted state β+*i* at time point β as *x*(β+*i* | β). A sequence of states will be indicated by *x*(·):

$$x(\beta+i)\ \forall\, i \in (0, \cdots, N_2) \Rightarrow x(\cdot),$$
$$w(\beta+i)\ \forall\, i \in (0, \cdots, N_u) \Rightarrow w(\cdot),$$
$$y(\beta+i)\ \forall\, i \in (N_1, \cdots, N_2) \Rightarrow y(\cdot).$$

The block diagram representation of the MPC based control system is shown in Fig. 2.

Results and Discussion

The parameters of the three-phase squirrel cage induction motor have been calculated by conducting the no-load test, blocked rotor test, moment of inertia test and the stator resistance test.[11,12] The parameters and specifications are arranged in Table 1. The name plate specification of the induction machine under consideration is given in appendix.

For the three-phase squirrel cage induction motor under consideration, the proportional plus integral controller (*P-I* controller) based control system for its torque control has been designed in the MATLAB/SIMULINK environment. The values of K_p = 0.9489 and K_i = 400 as obtained earlier were set in the PI block. After building and compiling the model, the results were obtained on the SCOPE, which are presented in the Fig. 3. For better visualization, the zoomed-out portions z_1, z_2 and z_3 have been shown along with this Figures.

From this figure, it can be concluded that though the electromagnetic torque settles down to the load torque value but there are occurrences of undershoots and overshoots. The delay time, rise time, peak time, settling time and maximum overshoot as obtained from this figure for are given in the Table 1. In order to overcome the shortcomings of the *P-I* controller, a novel control strategy, *i.e.*, Model Predictive Control has been designed in such a way, that the electromagnetic torque is controlled in the most effective manner. For the three-phase squirrel cage induction motor under consideration, the *MPC* controller is designed in the same environment.The values of sampling time, control horizon and prediction horizon which were set are respectively 0.001*s*, 2 and 10.

After building and compiling the model, the results of the simulation as obtained from the SCOPE are illustrated in Fig. 4. Similarly to the PI controller, the zoomed out portions have been shown for better visualization.

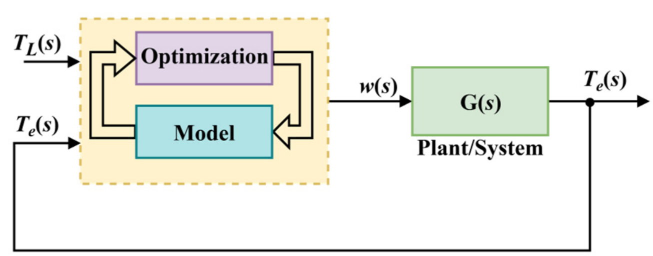

Fig. 2: Block diagram of MPC based control system

Table 1: Motor Parameters and Specifications

S. No	*Specifications and Parameters*	*Values*
1.	Rated Power (hp)	1
2.	Rated frequency (Hz)	50
3.	Number of pole pairs	2
4.	Per Phase Stator Resistance (Ω)	10.75
5.	Per Phase Stator Inductance (H)	0.048
6.	Per Phase Rotor Resistance (Ω)	11.06
7.	Per Phase Rotor Inductance (H)	0.048
8.	Per Phase Magnetizing Inductance (H)	0.904
9.	Moment of Inertia (kg-m^2)	0.0124

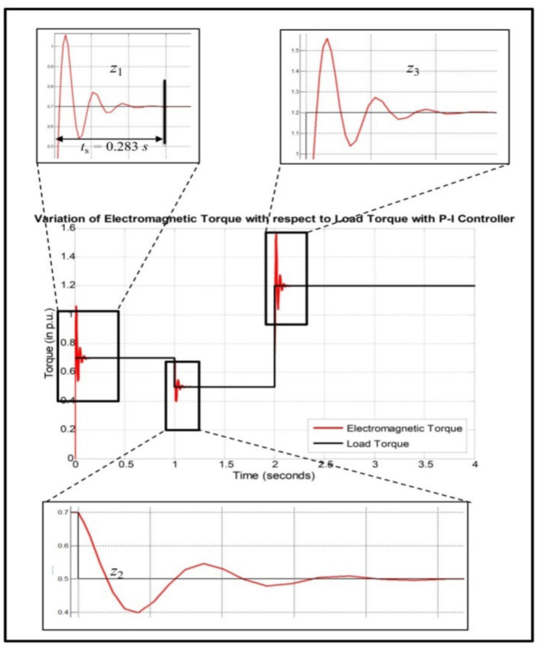

Fig. 3: Transient electromagnetic torque with respect to change in Reference Load Torque with PI controller

Fig. 5 on the other hand depicts the comparison of the SCOPE outputs with both the controllers. It can be clearly seen from the figure that MPC controller performs superior in comparison to PI controller in terms of overshoots, undershoots and settling time. The quantitative comparison

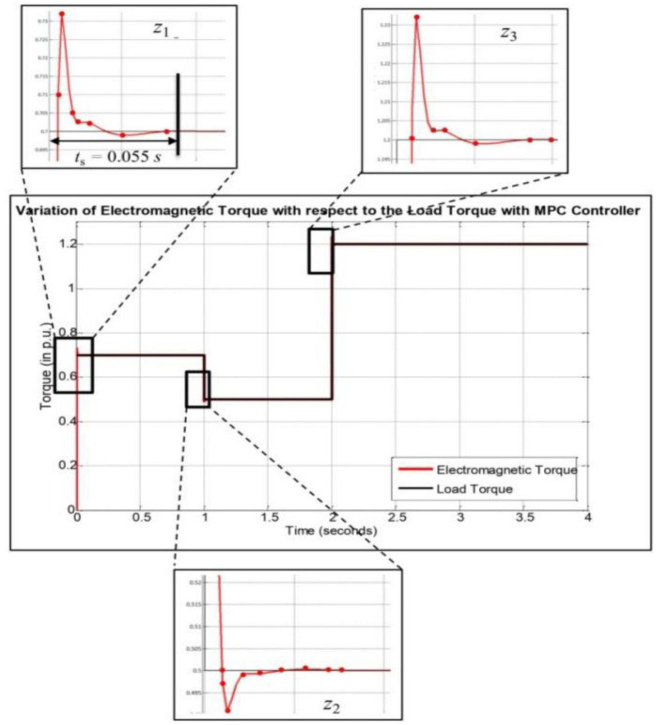

Fig. 4: Transient electromagnetic torque with respect to change in Reference Load Torque with MPC controller

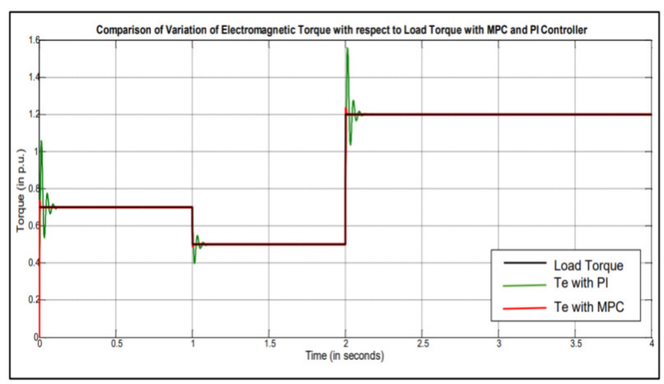

Fig. 5: Comparison of MPC controller and PI controller showing the transient electromagnetic torque with respect to change in Reference Load Torque

Table 2: Transient Response for the Induction Motor Control System For z_1

S. No.	*Transient Response **(for the first step change)***	*Value (with PI)*	*Value (with MPC)*
1.	Delay Time"	0.0016 sec	0.0011 sec
2.	Rise Time"	0.0143 sec	0.00215 sec
3.	Peak Time"	0.0159 sec	0.00398 sec
4.	Settling Time"	0.281 sec	0.055 sec
5.	Maximum Overshoot"	0.511	0.0457

of the results (for the first step change) as obtained with PI controller and with MPC controller is done based on delay time, rise time, peak time, settling time and maximum overshoot is shown in Table 2.

From the transient torque characteristics as presented in the Figures 3, 4 and 5, it is quite evident that there is significant reduction in the overshoots and undershoots with the MPC controller in comparison to the performance with the PI controller.

Also, the quantitative comparison as shown in Table 2 reveals that the settling time (the time within which the electromagnetic torque settles down to the load torque value), rise time and peak time with MPC controller are appreciably reduced, along with that the maximum overshoot with MPC controller is 4.57% and that with PI controller is 51.1%, which is laconically highlighting the fact that MPC controller is the perfect fit for the industrial drive systems where fine torque control of the induction motor is of paramount importance.

Conclusion

In this work, an advanced model predictive controller based strategy is proposed to effectively control the electromagentic torque developed by the three-phase squirrel cage induction machine. In addition, the classical PI controller is also developed and its comparison with proposed controller reveals the superiority of the proposed MPC based controller. This superiority is in terms of enhanced transient performance of the electromagnetic torque of the machine (refer Table 2). Therefore, this work highlights that MPC controller is the perfect fit for the industrial drive systems where fine torque control of the induction motor is of paramount importance.

Appendix

The name-plate specification of the induction motor under consideration is shown in Fig. 6.

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Fig. 6: Induction Motor name-plate specifications