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Reduction of Torque Ripples in Induction Motor Using Model Predictive Torque Control Method

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Abstract: Nowaday, model predictive based torque control is arise as one of the powerful control technique for the IM drives. The fast response and accuracy is the main features of predictive torque control technique. The control technique includes the predictive controller to obtain better dynamic response and PI controller to attain better steady state response. The main characteristics of PTC is by using the machine model for determining the future performance of the variables which is to be controlled. In MPTC scheme, the command signals are indicated as cost function, which is to be reduced. It has increased resilience to use constraints that gives low computational complexity compared to simple vector controlled schemes. PTC offers increased dynamic behaviour and improved speed responses. A modified MPTC is sugested for the control of the torque ripple minimization. A portion of time interval is given to the non zero voltage vector, while the remaining time is given for a zero vector. The minimisation of torque ripple concept help to know the time period for individual vectors. The proposed method proves that it gives excellent steady state response by the reduction of the torque ripples.

Keywords: Direct torque controls, induction motors, predictive torque controls.

I. INTRODUCTION

In former days, dc machines were widely used for adjustable speed drive applications because of the decoupled management of torque and flux that will be obtained by current control. DC drives has many merits like starting torque, speed variation, simple management and nonlinear performance. However due to the disadvantage of DC machine like the effect of commutator and brush assembly. In the industrial applications, DC machine drives are not used nowadays. AC motors are replaced by the DC motors due to their reduced price, excellent reliability, reduced heaviness, and maintenance requirement is less.

Direct Torque Control (DTC) is a type of better performance control strategy for the three phase ac electric drives [1]. DTC is commonly used method to adjust the torque in adjustable frequency drives such three phase ac machines. It includes calculating the motors torque and magnetic flux based on the measured current and voltage of the motor. Accuracy and fast torque performance is the main features. But, predefined switching tables and hysteresis comparators causes variable switching frequency and more torque ripple [2].

MPTC has developed as the best substitute to DTC by determining the future performance of the system under the constraints of less number of switching states of inverters [3]-[6]. By comparing with DTC, the predefined switching tables are altered by a precise system model. From which the electromagnetic torque and flux can directly predict. The influence of each feasible voltage vectors are evaluated and the one reducing the torque and flux errors is taken as the accurate voltage vector. Hence, the vector taken from MPTC is precise and accurate than that from DTC.

II.DYNAMIC EQUATIONS OF INDUCTION MOTOR

The dynamic equations of induction motor are represented in stationary frame as

$$u_s = R_s i_s + \frac{d\psi_s}{dt} \tag{1}$$

$$0 = R_r i_r + \frac{d\psi_r}{dt} - j\omega_r \psi_r \tag{2}$$

$$\psi_s = L_s i_s + L_m i_r \tag{3}$$

$$\psi_r = L_m i_s + L_r i_r \tag{4}$$

Where u_s, i_s, i_r, ψ_s, $\psi_r, R_s, R_r, L_s, L_r, L_m$ are stator voltage and current, rotor current, stator and rotor flux linkage, stator and rotor resistance, stator and rotor inductance, mutual inductance respectively; ω_r is the rotor speed.

$$i_s = \lambda(L_r \psi_s - L_m \psi_r) \tag{5}$$

$$i_r = \lambda(-L_m \psi_s + L_s \psi_r) \tag{6}$$

Where $\lambda = 1/(L_r L_s - L_m^2)$

Electromagnetic torque T_e of motor is represented as follows

$$T_e = \frac{3p}{2} \mathrm{Im}(\bar{\psi}_s i_s) \tag{7}$$

where p is the number of poles.

Moreover, the motion equation of motor is as follows

$$\omega_r(t) = \frac{p}{2j} \int (T_e - T_L) dt \tag{8}$$

III.PREDICTIVE CONTROL

Control based on model predictive can be represented as an algorithm. It can be used as a mathematical model inorder to anticipate its future behavior. The accurate control actions are given based on the optimality criterion. In power converters, the predictive controllers used in earlier days was the deadbeat predictive control. It avoids the classic linear controllers. The required reference voltages are calculated by using the machine model to reach the desired reference values for a certain variable (mainly the current). The expected reference voltages are then produced by the converter through a modulation stage [7].

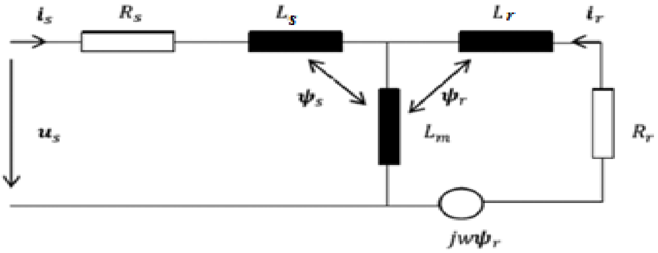

Fig.1. Equivalent circuit of induction motor

Predictive control has many merits so which make it useful for the power converter control: Idea is easy to understand and intuitive, it can be given to various conditions, multivariable situation can be included, and the controllers are easy to implement. The main characteristics of control using model predictive is the use of a machine model for the determination of its future condition of the variables to be controlled. Inorder to attain the optimal actuations the controller uses these information corresponding to an optimization criterion which is predefined. Controls based on deadbeat, hysteresis, trajectory and model predictive are the various methods for predictive control. In trajectory based optimization criterion control method the controlled variable is tends to follow a predefined trajectory [7] whereas in hysteresis predictive control method is to maintain the variables within the hysteresis circle [8]. In dead-beat predictive control method, the actuations are the one that adjust the error become null in the coming sampling time [9]. The only demerit is that it requires a modulator and constraint are not being included directly. The optimization in MPC is represented as cost function to be reduced [10]. In proposed paper, the algorithm used is predictive control. The method is called predictive torque control method. The typical Predictive torque control technique uses a cost function with series combination of the control functions to get perfect voltage vector to obtain in the upcoming sampling time. Weighting factor is also considered to include the flux and the torque error in cost function.

IV.MODEL PREDICTIVE CONTROL

The general concepts of Model predictive control are, a model of machine is used to guess the future performance of the controllable variables till a time range, a cost function that consider the appropriate performance of the systems and the proper actuations are selected by minimising cost function [8]. MPC is an optimization problem that includes minimization of the cost function g, for a known time range, subjects to the system limitations and the model of the system. The results are string of optimal actuations. The controller will take only the initial component of the string.

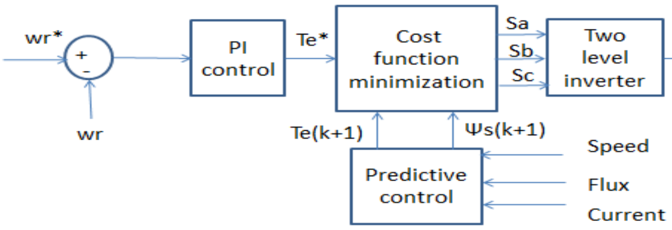

Fig.2. Proposed System

In conventional MPTC, single voltage vector is choosed and it is given during single control period. As a result of restricted voltage vectors in two-level inverter, this unsuccessful to decrease the torque ripple to the lower value. So, the frequency of MPTC has to be large in order to attain proper steady state performance. It has been known in DTC that the zero vectors produce few torque variation. Hence, it is possible to handle both an active vector and a non-active vector during single control span to obtain the reduction of torque ripple [4]. The proposed MPTC tries to embrace this principle by splitting the control span into two intervals for both vectors. Figure 2 shows the overall control diagram of the proposed MPTC, which consist of three parts: prediction and estimation of flux and torque, cost function minimization or selection of vector, and reduction of torque ripple.

A. Estimation and prediction of flux and torque

With small sampling time, we can use first-order Euler equation $\dot{x}(k) = (x(k+1) - x(k))/T_s$ to transform equation (7) into discrete form.

$$T_e(K+1) = \frac{3p}{2}\mathrm{Im}(\bar{\psi}_s(K+1) * i_s(K+1)) \qquad (9)$$

B. Vector selection

The selection of vector is represented on the principle of minimisation of a cost function, which is composed of series combination of torque and flux errors. The cost function is

$$g = |T_e^{ref} - T_e^{k+1}| + A.\,||\psi_s^{ref}| - |\psi_s^{k+1}|| \qquad (10)$$

Where T_e^{ref} and ψ_s^{ref} are the reference torque and stator flux amplitude; A is the weighting factor for the stator flux.

Eight discrete voltage vectors are available for Induction motor drives with two-level inverter: V_0, V1, ..V_6, V_7. For each individual voltage vector, we can find a value of T_e^{k+1} and ψ_s^{ref} , and the one reducing (10) is taken as the voltage vector to be applied. There is a step delay between actual voltage and commanding voltage in real time implementation [11]. To take care of this delay, the variables at time instant (k + 2)th should be used rather than (k + 1)th time period, which have a two-step prediction [11]. This paper employs a model-based prediction. The stator parameter like current and flux at (k + 2)th instant are predicted with their (k + 1)th value as initial condition.

The toque at (k+2)th instant is

$$T_e(K+2) = \frac{3p}{2}\mathrm{Im}(\bar{\psi}_s(K+2) * i_s(K+2) \qquad (11)$$

Therefore, the cost function with one-step delay is modified from (10) to (12):

$$g = |T_e^{ref} - T_e^{k+2}| + A.\,||\psi_s^{ref}| - |\psi_s^{k+2}|| \qquad (12)$$

C. Torque Ripple Minimisation

The interval of nonzero vector must determine after the selection of active voltage vector based torque ripple reduction principle.

Duration of the torque ripple in one control period can be represented as:

$$\frac{1}{T_{sc}}\int_{kT_{sc}}^{(k+1)T_{sc}}(T_e^{ref}-T_e)^2\,dt \rightarrow \min \tag{13}$$

A pictorial representation of time instants used in the control algorithm is shown in Figure 3. The torque is predicted for a particular voltage vector applied at time k, along with the measurement of current at time k is shown in figure 3(a). However, almost complete period is needed for calculating the optimal voltage vector in the real implementation, as shown in figure 3(b), and the same voltage vector calculated assuming to be given at time k is given at time k + 1. To consider this delay, prediction must deal with the actuation to be given at time k + 1, and the response of this voltage in the upcoming torque value must be examined at k + 2th time instant, as shown in figure 3(c).

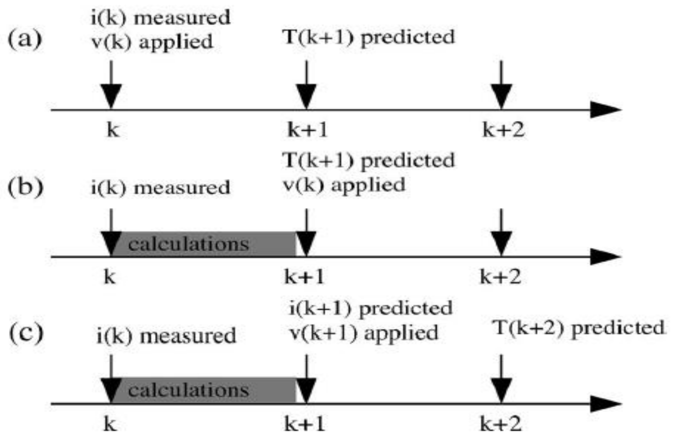

Fig.3.Time period for the algorithm (a) Real case (b) without compensation (c) With compensation of the delay.

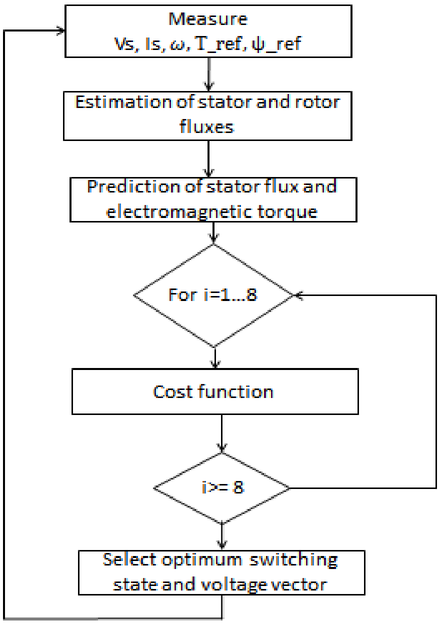

Fig.4. MPTC Algorithm

V. SIMULATION AND RESULTS

A. Modeling of Induction motor

A 4 kW induction motor [8] is modeled with machine details specified in Table1.

TABLE 1 .MACHINE PARAMETERS

Rated power, P	4 Kw
Rated voltage, U	380 V
Rated frequency, f	50 Hz
Rated torque, T	10 Nm
Pole pair	2
Stator resistance, Rs	3.126 Ω
Rotor resistance, Rr	1.879 Ω
Stator inductance, Ls	.230 H
Rotor inductance, Lr	.230 H
Mutual inductance, Lm	.221 H

Figure 5 shows the modeling of IM according to the equations 1 to 8. The results obtained are as follows. Figure 6 shows the three phase input voltage given to the induction motor. Figure 7 shows the waveforms of current, of an induction machine. A step time of 0.7 sec is given to the machine, as a result up to 0.7 sec the graphs shows the no load reading and after 0.7 sec loaded condition is depicted here. The peak value of the current is about 10.2 A obtained. Figure 8 and 9 shows the electromagnetic torque and speed of induction motor respectively. At time 0.7 sec, speed is decreased and torque is increased.

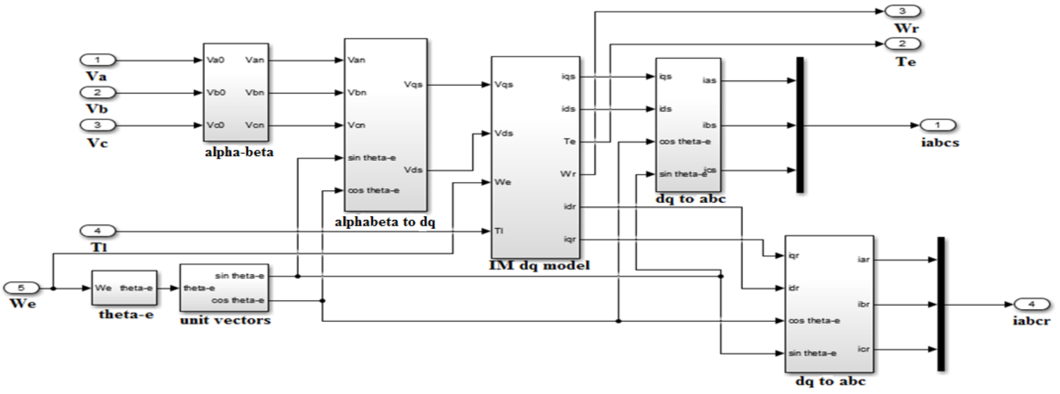

Fig.5. MATLAB modeling of induction motor

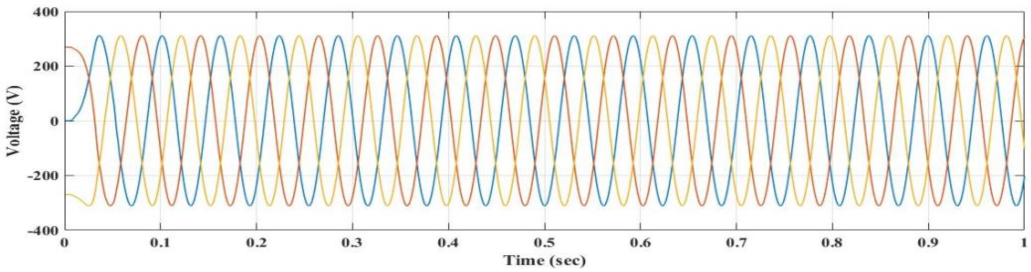

Fig.6. Three phase voltage

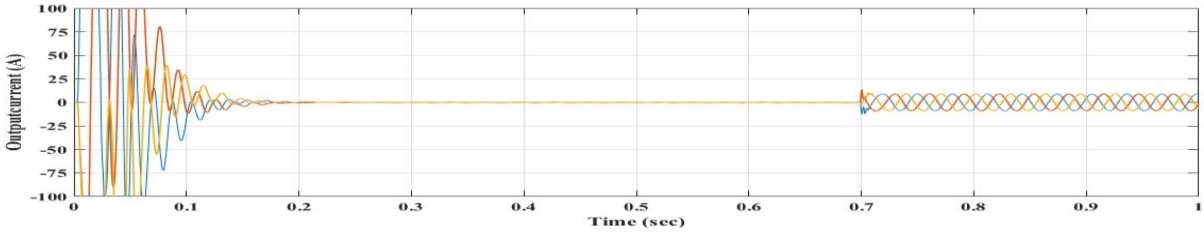

Fig.7. Three phase output current

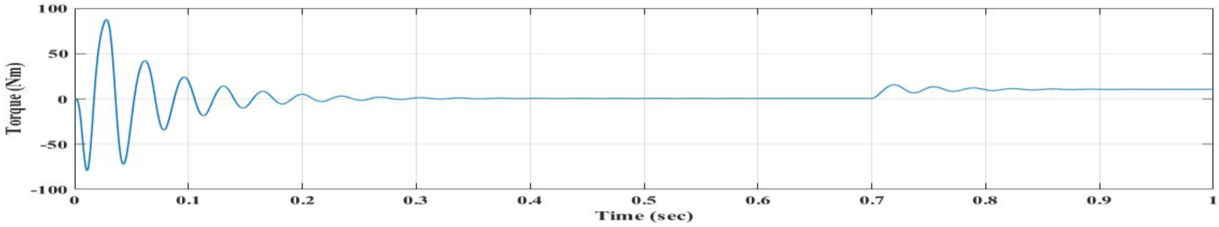

Fig.8. Electromagnetic torque

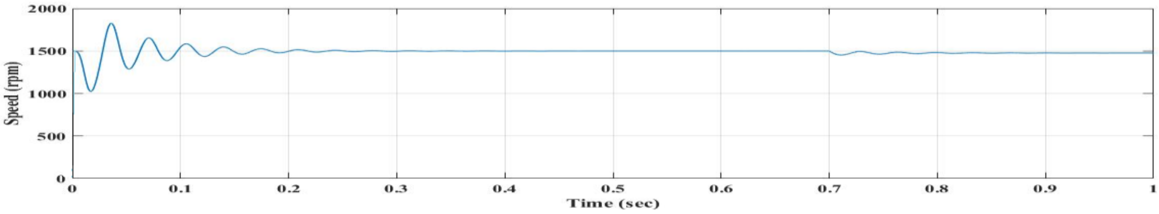

Fig.9. Speed of induction motor

B. Modeling of Induction motor with PI controller

Figure 10 shows the modeling of induction motor with PI controller. Figure 11 shows the output current obtained from the above modeling. Figure 12 and 13 shows the torque and speed obtained.

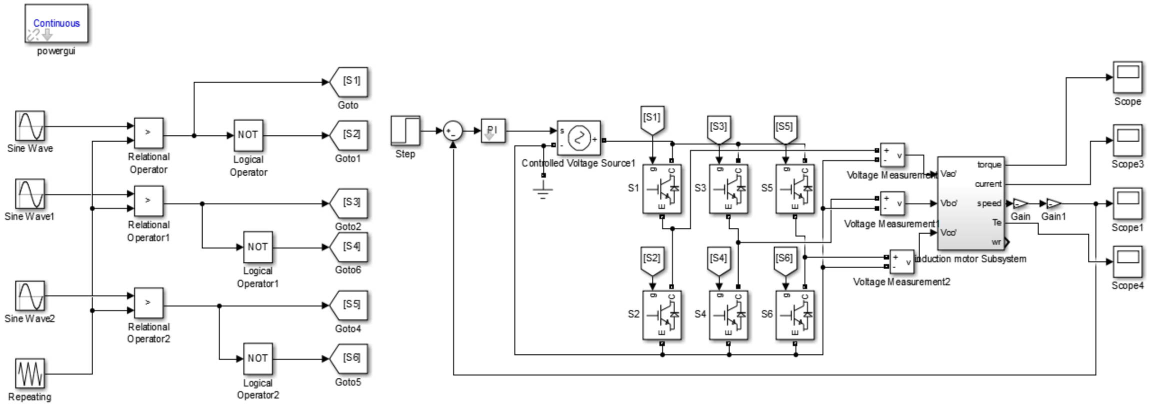

Fig.10. Modeling of induction motor with PI controller

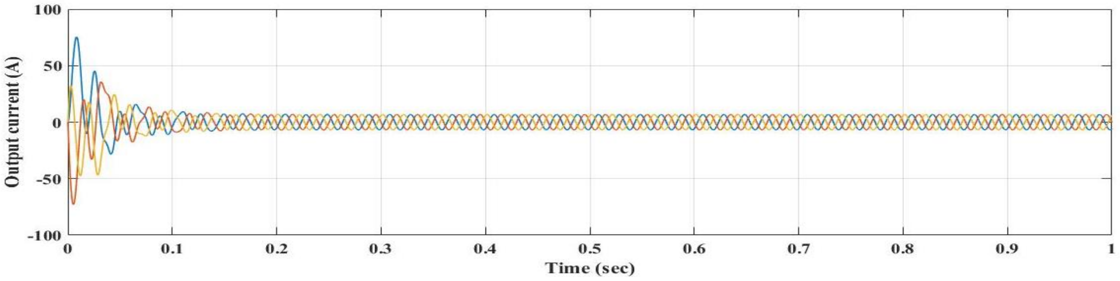

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Fig.11. Output current

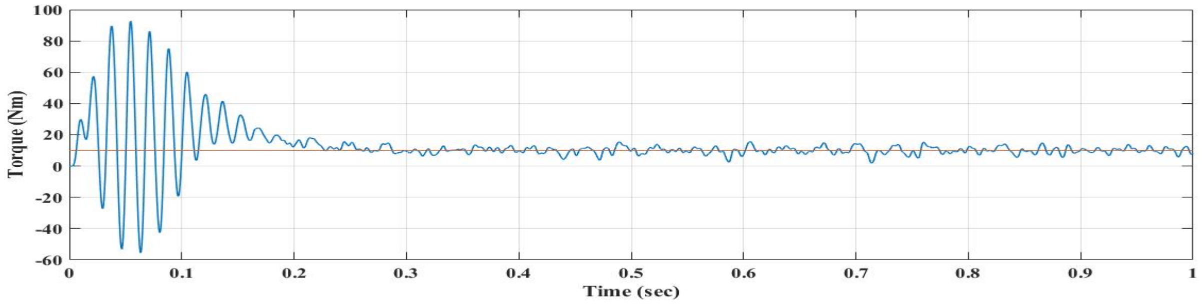

Fig.12. Torque characteristics

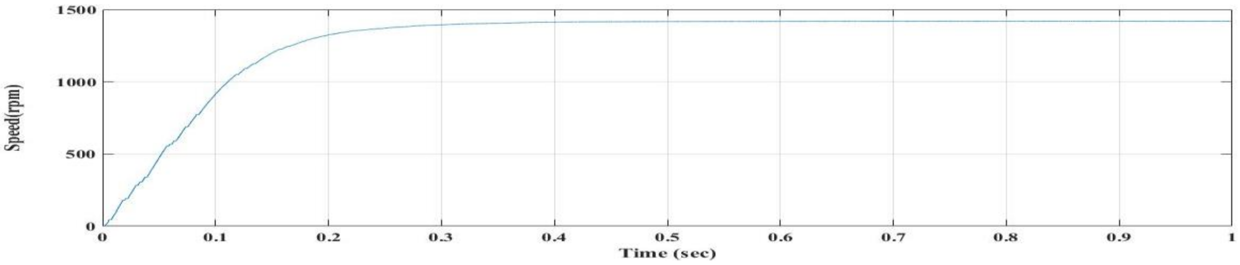

Fig.13. Speed characteristics

C. Modelling of MPTC control

Figure 14 shows the modeling of proposed model predictive torque control. Figure 15 shows the output current obtained from the above modeling. Figure 16 and 17 shows the torque and speed obtained.

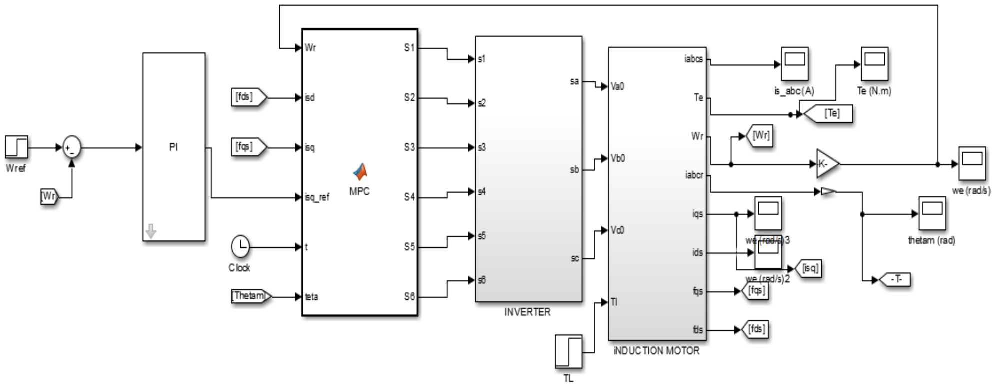

Fig. 14. Proposed MPTC

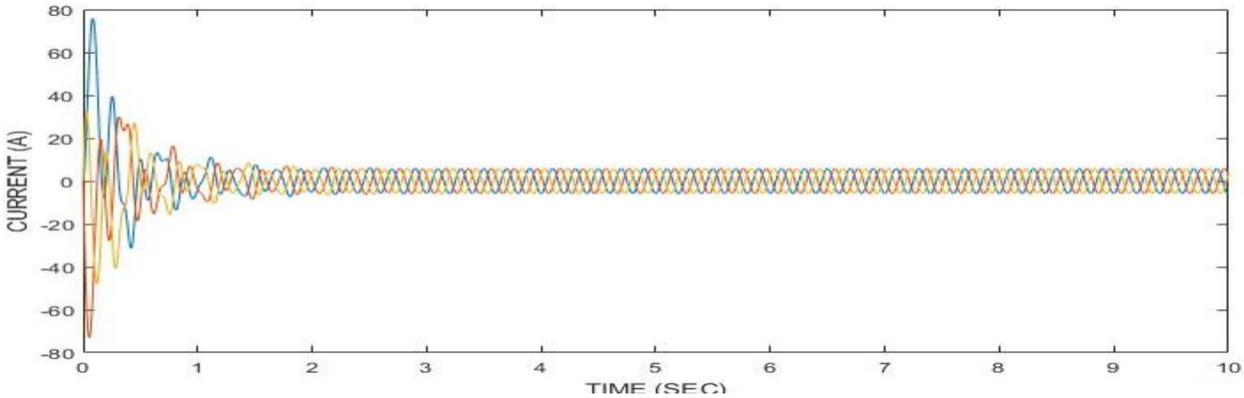

Fig.15. Current waveform

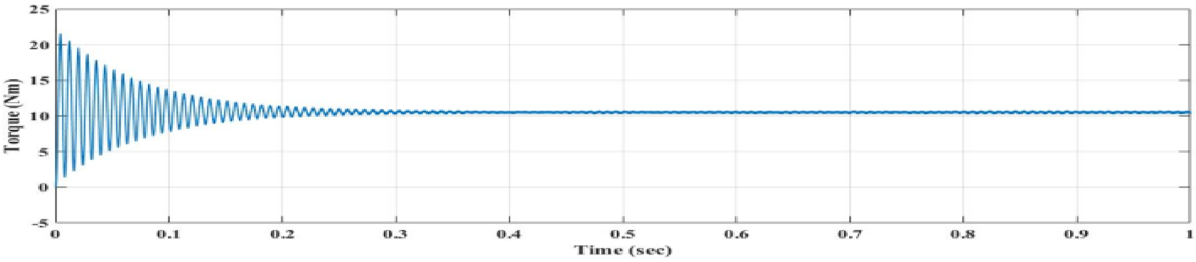

Fig. 16. Torque characteristics at full load

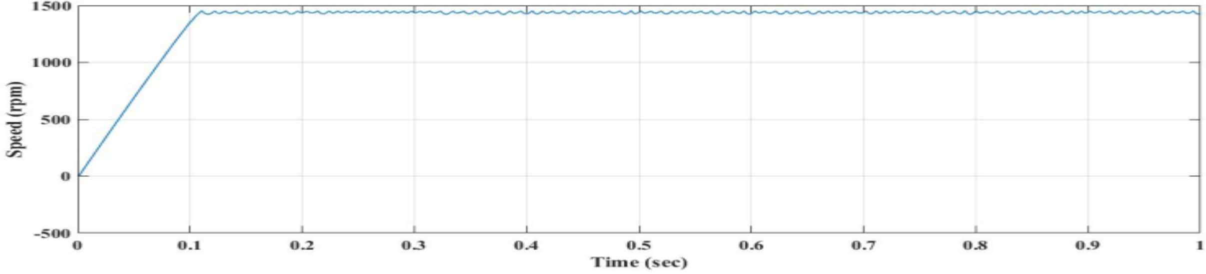

Fig.17. Speed characteristics at full load

VI. CONCLUSION

An efficient MPTC is used to achieve the reduction of torque ripple was proposed. For that purpose, the control period is splitted into two intervals. One is for appropriate null vector and other one for active vector. The control period of the nonzero vector is achieved with torque ripple minimization strategy. Individual control of torque and stator flux can be achieved with good dynamic performances and steady state behavior. By comparing the torque ripples in PI controller based induction motor and MPTC, the torque ripple is reduced from 0.6 to 0.06.

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