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Predictive Torque Control Of Induction Motor

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ABSTRACT: Variable-speed induction motor drives are increasingly being used in most of the industrial applications. The development of high performance control strategies for AC drives, driven by the requirement of industry, has resulted in a rapid evolution during the last two decades. The Predictive Torque Control (PTC) technique has features of precise and quick torque response. This method is gaining popularity in the industry due to its simplicity and high dynamic performance. The control strategy combines the use of classical PI controller to obtain good steady state response and a predictive controller scheme to achieve good dynamic response. The main characteristic of predictive control is the use of a model of the system for predicting the future behavior of the controlled variables. This information is being used by the controller to obtain the optimal actuation, according to a predefined optimization criterion. In predictive control scheme, the control objectives are defined as a cost function, which is to be minimized to have greater flexibility to include constraints which results in low computational complexity compared to simple vector controlled schemes likes FOC and DTC scheme. PTC offers high dynamic performance, accurate speed response. The PTC based voltage source inverter fed induction motor drive is capable of offering four quadrants in the torque-speed plane of operation like, forward motoring, forward generating, reverse generating and reverse motoring. To validate the proposed algorithms mathematical models were developed for induction motor, estimation of torque and flux and control logic. These models were integrated and simulations were carried out using Matlab/Simulink. Variation in stator currents, speed, electro-magnetic torque developed and stator flux during different operating conditions such as starting, steady state, sudden change in load and speed reversal are observed with the help of waveforms and results are discussed.

KEYWORDS: Predictive Control, Induction Motor, electromagnetic torque, Control strategy.

I. INTRODUCTION

The electrical machine that converts electrical energy into mechanical energy and mechanical energy into electrical energy is the workhorse in a drive system. Electrical motors play a key-role in the transportation industry. Drive systems are widely used in applications such as pumps, fans, paper and textile mills, elevators, electrical vehicles and subway transportation, home appliances, wind generation systems, servo and robotics, computer peripherals, steel and cement mills, ship propulsion, etc. Applications driven by electric drives require more or less advanced control strategies. Design and analysis of all electric drive systems require not only knowledge of dynamic properties of different motor types, but also a good understanding of the way these motors interact with power electronic converters. Industrial drive applications are generally classified into constant and variable speed drives. Variable speed drives are used in all industries to control precisely the speed of electric motor driving loads ranging from simple pumps and fans to complex drives on paper machines, rolling mills, cranes and similar drives. In order to understand the requirements for adjustable speed drives, an overview about the fields of electrical motor applications is specified. Important factors, affecting the choice of an adjustable speed drive, include among others are, rating, cost, speed range, efficiency, speed regulation, braking requirements, reliability, power factor, power supply availability, environmental considerations. The basic applications of electrical motors show that motion control of an electrical machine can be focused to one or more of the following objectives: speed, torque and position control. The electrical machines currently used for speed control applications can be categorized as direct current (DC) machines, alternating current (AC) machines.

DC machines have been in service for more than a century. They were used extensively in variable speed applications to give a fast and good dynamic torque response because the commutator maintains a fixed or nearly constant torque angle at all times. DC machine drive converters and controls are simple, and the torque response of the machine is very fast. Among the widely used DC motor drives, separately excited DC motors were the suitable choice for variable speed applications. These have been considered as a main workhorse in the industry. This is due to its faster dynamic performance as compared to AC motors. The faster dynamic performance of the motor is because of its being a doubly fed motor along with inherent facility of decoupled control of torque and flux in the motor. The commutator and brush assembly makes the developed torque proportional to the armature current if the field current is maintained constant. Some important applications of DC drives are rolling mills, paper mills, mine winders, hoists, machine tools, traction, printing presses, textile mills, excavators, cranes etc. However, DC machines have two major weaknesses, the mechanical commutator and brush assembly. These make periodical maintenance a must and limit the use of DC machines. Also DC machines are comparatively costly

II. PREDICTIVE CONTROL

Induction motors have been in use for over hundred years, because of their simplicity, ruggedness, reliability, efficiency, low cost, compactness and economical. Recent developments in the field of variable speed drives have made possible the large-scale application of variable speed induction motor drives. High dynamic performance, instantaneous electromagnetic torque control induction motor drives have been used for few decades. The idea of MPC were developed in 1960s as an application of optimal control theory, industrial interests in these ideas started in the late 1970s. Model Predictive control is an advanced method of process control that has been in use in the process industries, in chemical plants, and oil refineries since the 1980's. In recent years it has been also used in power system balancing models. Model predictive controllers rely on dynamic model of the process, most often linear models obtained by system identification. The advantage of MPC is the fast that it allows the current timeslot to be optimized by keeping future timeslots in account. This is achieved by optimizing a finite time-horizon, but only implementing the current timeslot.MPC has the ability to anticipate future events and can take control actions accordingly. MPC is digital control.MPC is based on iterative finite horizon optimization of plant model. At time t the current plant state is sampled and a cost minimizing control strategy is computed (via a numerical minimization algorithm) for a relatively short time horizon. MPC has the ability to anticipate future events and can take control actions accordingly.

A.Model Predictive Control for Power Electronic Drives

Although the theory of MPC was developed in the 1970s, its application in power electronics and drives is more recent due to the fast sampling times that are required in these systems. The fast microcontrollers available in the last decade have triggered research in new control schemes, such as MPC, for power electronics and drives. In MPC a model of the system is considered in order to predict the future behaviour of the variables over a time frame (integer multiple of the sample time). These predictions are evaluated based on a cost function, and then, the sequence that minimizes the cost function is chosen, obtaining, in this way, the future control actions. Only the first value of the sequence is applied, and the algorithm is calculated again every sampling period. MPC has several advantages, such as the easy inclusion of nonlinearities and constraints. This scheme has few applications in power converter control and drives due to the high amount of calculations needed in order to solve the optimization problem online, which is incompatible with the small sampling times used in converter control. One solution in order to reduce the calculation time is to solve the optimization problem offline, as presented in [1], where MPC is implemented as a search tree and the calculation time is reduced, making it possible to use the MPC in drive control. Another solution is the use of Generalized Predictive Control (GPC) [2], where the optimization is solved analytically, obtaining a linear controller. Nevertheless, with GPC, it is very difficult to include system constraints and nonlinearities.

Another approach for implementing MPC for power converters and drives is to take advantage of the inherent discrete nature of power converters. Since power converters have a finite number of switching states, the MPC optimization problem can be simplified and reduced to the prediction of the system behaviour only for those possible switching states. Then, each prediction is used to evaluate a cost function (also known as quality or decision function), and consequently, the state with minimum cost is selected and generated. This approach is known as a Finite Control

Set MPC (FCS-MPC), since the possible control actions (switching states) are finite. This method is also known as finite alphabet MPC or simply as predictive control, and it has been successfully applied to a wide range of power converter and drive applications [3]–[5].

B.Predictive Torque Control

The most widely used linear strategy in high performance electrical drives is field oriented control (FOC) [6]-[8], in which a decoupled torque and flux control is performed by considering an appropriate coordinate frame. A non linear hysteresis-based strategy such as direct torque control (DTC) [9] appears to be a solution for high performance applications. At the end of the 1970s, model predictive control (MPC) was developed in the petrochemical industry [10]-[12]. The term MPC does not imply a specific control strategy, but covers an ample variety of control techniques that make explicit use of a mathematical model of the process and minimization of an objective function [13] to obtain the optimal control signals.

The concept of MPC is based on the calculation of the future behaviour of the system, in order to use this information to calculate optimal values for the actuating variables. Execution of the predictive algorithm can be divided into three main steps: estimation of the variables that cannot be measured, prediction of the future behaviour of the system, and optimization of outputs, according to a previously designed control law.

For motor drive applications, the measured variables **i**s , ω, and a mathematical model of the machine are used to estimate the variables that cannot be measured, such as the rotor and stator flux λ_r , λ_s . Then, the same model is used to predict the future behaviour of the variables for every control action. Finally, the voltage vector that produces the optimum reference tracking is selected as the switching state for the next sampling step. The model of the machine is the most important part of the controller, because both estimations and predictions depend on it.

Predictive control has many advantages that make it a real option if high dynamic control of electrical drives is required. The concept is easy to understand and implement, constraints and nonlinearities can be included, and multivariable cases can be considered. This control scheme requires lots of calculations compared to traditional strategies. Fortunately, the performance of current processors is sufficiently powerful to make this approach possible. The main difference between predictive control and traditional strategies is the pre- calculation of the system behaviour, and its consideration in the control algorithm before the difference between the reference and the measured value occurs. The feedback PI- control loop corrects the control difference when it has already appeared.

The block diagram of PTC motor drive [14] employing a 2L-VSI is as shown in the fig.2.1

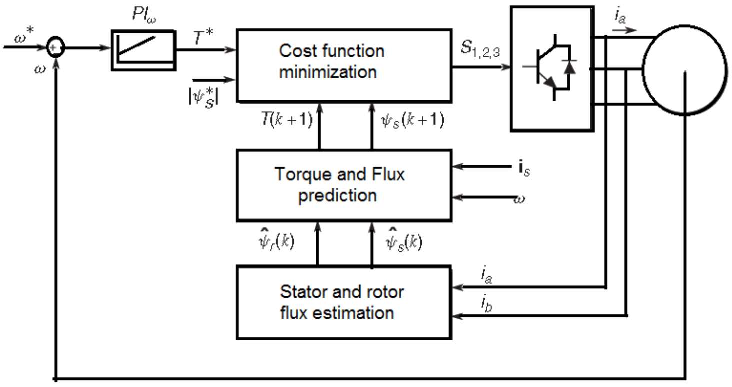


Fig.2.1. PTC scheme

III. INDUCTION MOTOR MODEL

The per-phase equivalent circuit of the induction machine is valid only for steady state analysis only. But in the case of adjustable speed drive, the machine normally constitutes an element with feedback loop, and therefore its transient behaviour has to be taken in to consideration. Besides a high performance drive control, such as FOC, DTC are based on the dynamic d-q model of the machine therefore in order to understand such techniques or to implement these techniques a good understanding of the d-q model is compulsory [15].the dynamic performance of AC machine is somewhat complex because the three phase rotor windings move with respect to the 3-phase stator windings as shown in Fig. 3.1.

The following assumptions are made in deriving the dynamic model of the induction motor.

They are

- Uniform air gap.
- Balanced rotor and stator windings, with sinusoidally distributed mmf.
- Inductance vs. Rotor position is sinusoidal, and
- Saturation and parameter changes are neglected.

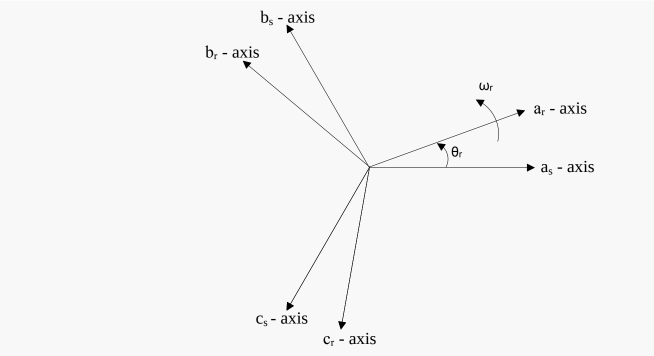


Fig. 3.1 Coupling effect in 3-phase stator and rotor windings of motor

According to the principle of coordinate transformations, the d-q method is to transfer one coordinate with a difference of 120 degrees for two of three phases to the d-q coordinate with a difference of 90 degrees for the d and the q coordinates. Between the stator and rotor of an AC induction motor, the coupling variables can be decoupled with the rotation reference coordinate. As a result, motor variables such as voltage, current, and flux linkage can be expressed as components perpendicular each other referred to as the direct axis (d axis) and the quadrature axis (q axis), respectively. As shown in figure 3.1, the relationships between the $a_s - b_s - c_s$ axis and the $d - q$ axis of a three-phase induction motor's stator is described as follows in case that the rotational speed of the $d - q$ axis is ω and the angle between the d axis and the a_s axis is θ hypothetically:

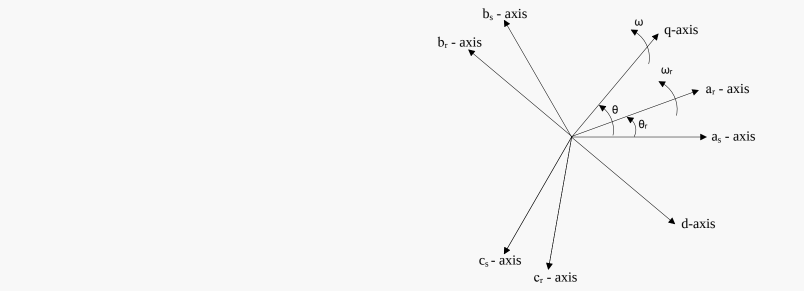


Figure 3.2 Relation diagram for stator axis, rotor axis and d-q axis of a three-phase induction motor.

Referring to figure 3.2, one is able to acquire the relationships between the stator's coordinate and d- q axis of the rotation coordinate.

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^0) & \sin(\theta - 120^0) & 1 \\ \cos(\theta + 120^0) & \sin(\theta + 120^0) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} \qquad (3.1)$$

The corresponding inverse relation is as follow

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^0) & \cos(\theta + 120^0) \\ \sin\theta & \sin(\theta - 120^0) & \sin(\theta + 120^0) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \qquad (3.2)$$

Here v_{os}^{s} is zero-sequence component. This zero sequence component does not exist in the case of a balanced induction motor having a balanced supply.

As shown in (3.3), the angle θ in (3.1) and (3.2) is the integral of ω, an arbitrary angular frequency of d - q axis.

$$\theta = \int \omega\, dt \qquad (3.3)$$

In this three-phase equilibrium power system, the three-phase voltage formulas for an induction motor's stator and rotor are shown in (3.4) and (3.5):

$$\overrightarrow{v_{abc}^s} = R_s \overrightarrow{i_{abc}^s} + \frac{d\overrightarrow{\lambda_{abc}^s}}{dt} \qquad (3.4)$$

$$\overrightarrow{v_{abc}^r} = R_r \overrightarrow{i_{abc}^r} + \frac{d\overrightarrow{\lambda_{abc}^r}}{dt} \qquad (3.5)$$

Taking the Euler's transform $\overrightarrow{v_{qd}^s} = e^{-j\theta}\, \overrightarrow{v_{abc}^s}$ and $\overrightarrow{v_{qd}^r} = e^{-j(\theta - \theta_r)} \overrightarrow{v_{abc}^r}$

and substituting (3.4) and (3.5) into (3.1) for further deduction, the voltage formulas for

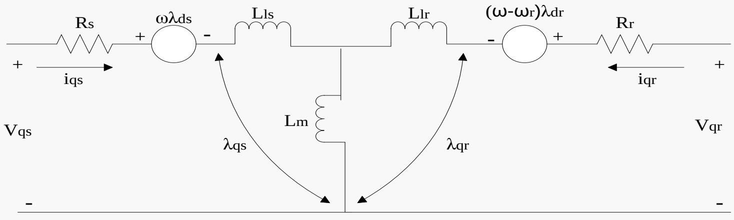
an induction motor's stator and rotor at the d − q axis are:

$$\overline{v_{ds}} = R_s \overline{i_{ds}} + \frac{d\overline{\lambda_{ds}}}{dt} - \omega \overline{\lambda_{qs}} \qquad (3.6)$$

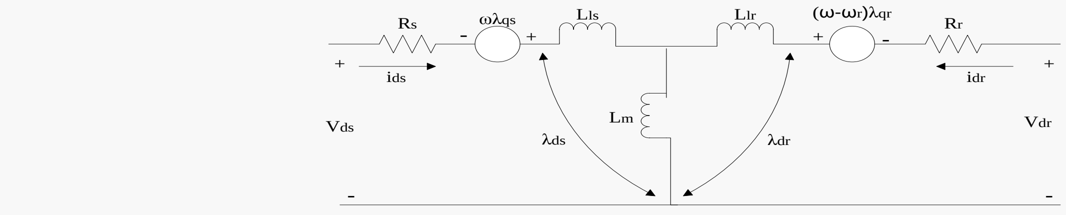
$$\overline{v_{qs}} = R_s \overline{i_{qs}} + \frac{d\overline{\lambda_{qs}}}{dt} + \omega \overline{\lambda_{ds}} \qquad (3.7)$$

$$\overline{v_{dr}} = R_r \overline{i_{dr}} - (\omega - \omega_r)\overline{\lambda_{qr}} + \frac{d\overline{\lambda_{dr}}}{dt} \qquad (3.8)$$

$$\overline{v_{qr}} = R_r \overline{i_{qr}} + (\omega - \omega_r)\overline{\lambda_{dr}} + \frac{d\overline{\lambda_{qr}}}{dt} \qquad (3.9)$$



(a) q – axis equivalent circuit



(b) d – axis equivalent circuit

Fig. 3.3. Induction motor equivalent circuit in a arbitrary reference frame

With equations from (3.6) to (3.11) integrated, formulas for this induction motor's voltage, current, and flux at this rotation coordinate are shown in (3.12).

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega L_s & L_m p & \omega L_m \\ -\omega L_s & R_s + L_s p & -\omega L_m & L_m p \\ L_m p & (\omega - \omega_r) L_m & R_r + L_r p & (\omega - \omega_r) L_r \\ -(\omega - \omega_r) L_m & L_m p & -(\omega - \omega_r) L_r & R_r + p L_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{3.12}$$

Where R_s , R_r and L_s , L_r are the resistances and self inductances of stator, rotor respectively, L_m is the mutual inductance between stator and rotor windings and $'p'$ is the differential operator.

It is observed that even though the order of the impedance matrix reduces considerably with the three phase to two phase transformation, the inductance coefficients are still time varying. Hence, simple routine procedures of inversion for finding the inverse are not very easily applicable. There is a necessity to linearise the equations to obtain constant coefficients. In 1920's R.H. Park proposed a new theory of electrical machine analysis to solve this problem. He transferred or referred the stator variables to a reference frame fixed to the rotor. Afterwards, in 1930's H.C. Stanley transferred the rotor variables to a frame of reference fixed in the stator. Further, G. Kron transferred the both stator and rotor variable to a reference frame rotating in synchronism with the rotating magnetic field. This reference frame is commonly referred as the synchronously rotating reference frame. It is clear that the time varying inductances can be eliminated by referring the stator and rotor variables to a common reference frame which rotates at zero, rotor, synchronous or an arbitrary reference speed. Thus, the induction motor model can be developed in any of the four reference frames and they are

- Rotor reference frame
- Stationary or stator reference frame
- Synchronously rotating reference frame.
- Arbitrary reference frame

This can be accomplished using a linear transformation that transforms all the variables to one reference frame i.e. rotating to fixed or vice versa and is shown in (3.13)

$$\begin{bmatrix} v_{\mathrm{dr}} \\ v_{\mathrm{qr}} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} v_{\mathrm{ar}} \\ v_{\mathrm{br}} \end{bmatrix} \tag{3.13}$$

Here dr - qr correspond to rotor direct and quadrature axes stationary with respect to stator. Among the different reference frames, PTC technique employs the stationary reference frame. Hence, in this project, dynamic model of the induction motor is developed in the stationary reference frame, which is also known as Stanley reference frame. Assuming the reference frame fixed to the stator, the rotor quantities can be referred to stator frame using (3.13). i_{dr} and i_{qr} are the currents in the fictitious coils whose axes are stationary with respect to the stator. This is equivalent to placing brushes and representing the rotor winding by means of pseudo-stationary coils. The transformation is referred as commutator transformation. Applying this transformation to the stator and rotor voltage equations, yields the mathematical model of 3-phase induction motor expressed in stator reference frame and is given by

$$\overline{v_{ds}} = R_s\overline{i_{ds}} + \frac{d\overline{\lambda_{ds}}}{dt} \quad (3.14)$$

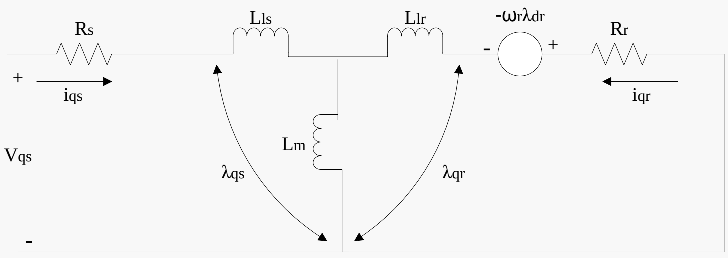
$$\overline{v_{qs}} = R_s\overline{i_{qs}} + \frac{d\overline{\lambda_{qs}}}{dt} \quad (3.15)$$

$$\overline{v_{dr}} = R_r\overline{i_{dr}} + \omega_r\overline{\lambda_{qr}} + \frac{d\overline{\lambda_{dr}}}{dt} \quad (3.16)$$

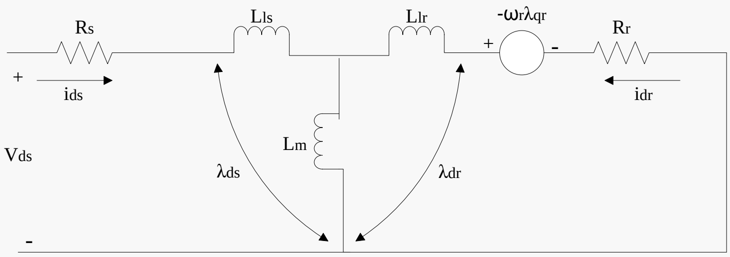
$$\overline{v_{qr}} = R_r\overline{i_{qr}} - \omega_r\overline{\lambda_{dr}} + \frac{d\overline{\lambda_{qr}}}{dt} \quad (3.17)$$

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & -\omega_r L_m & R_r + L_r p & -\omega_r L_r \\ \omega_r L_m & L_m p & \omega_r L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (3.18)$$

The induction motor's equivalent circuits for d – q axis in the stationary reference frame with cylindrical cage rotor.



(a) q – axis equivalent circuit



(b) d – axis equivalent circuit

Fig.3.4. Induction motor equivalent circuit in a stationary reference frame

IV. RESULTS

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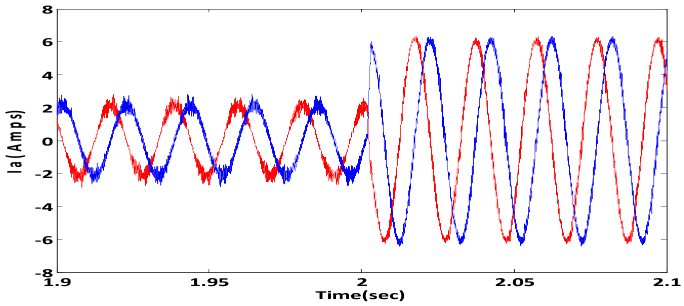
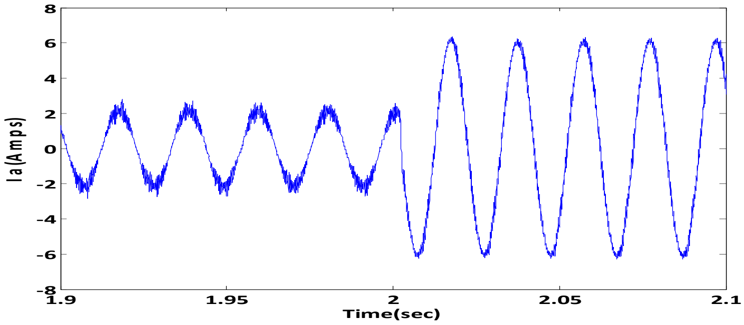
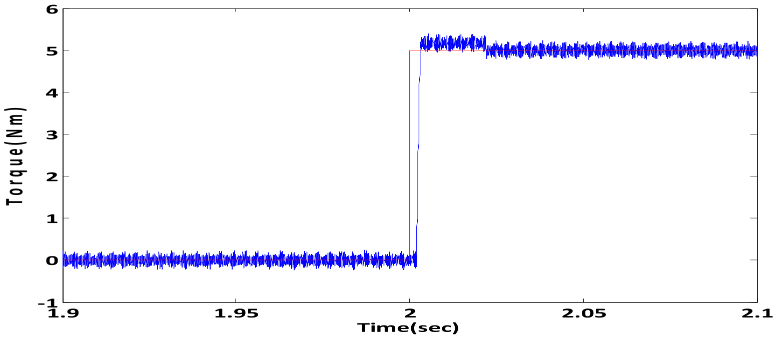
Operation of Drive System on Load



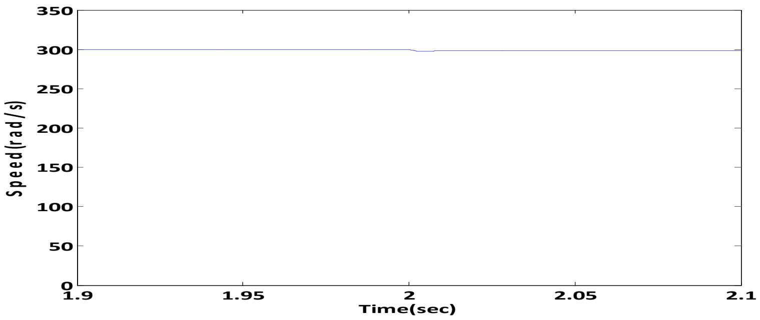
Stator currents _q_d



Stator current



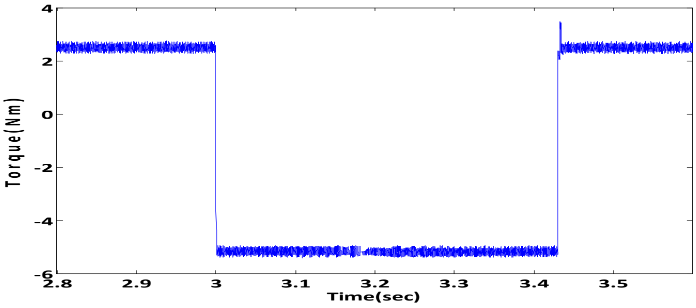
Torque



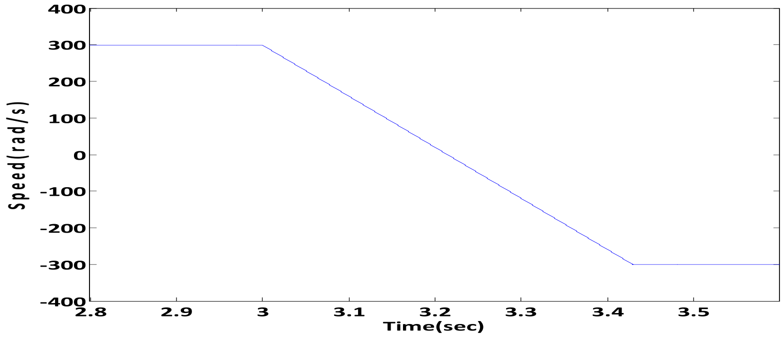
Speed

Transients during step change in load. 5 N-m is applied at 2 sec

Speed Reversal Operation



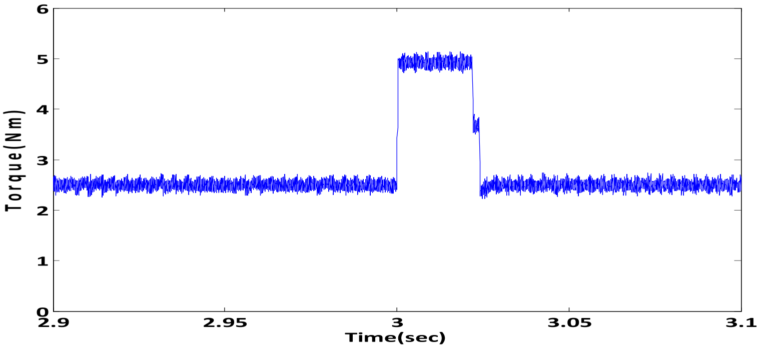
Torque



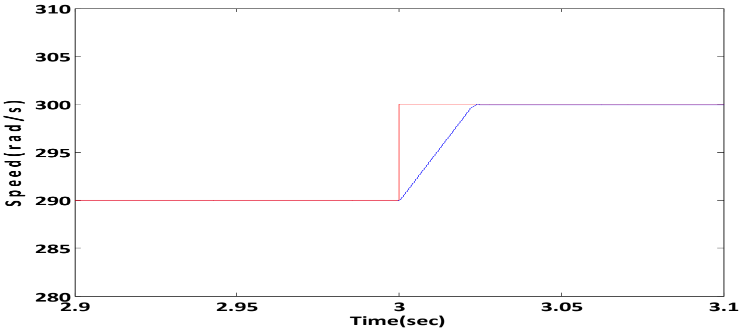
Speed

Transients during speed reversal operation of PTC drive

Reference Speed Tracking



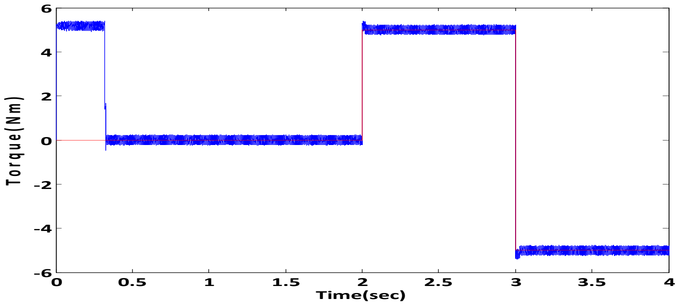
Torque



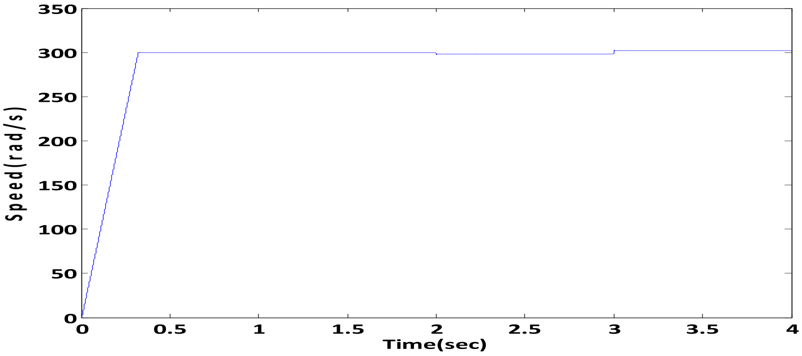
Speed

Behaviour during speed reference tracking

Torque Reversal Operation



Torque



Speed

PTC drive behaviour during torque reversal operation

V. CONCLUSION

In this project a detailed study of PTC induction motor drive was presented. In the predictive control scheme, the control objectives are defined as a cost function, which is to be minimized, and having greater flexibility to include constraints which results in low computational complexity. The simulation results presented here show the effectiveness of prediction scheme, i.e the diminishing torque ripple at different loads and speeds. From these results it is noted that PTC gives better results than the vector controlled induction motor drive. The advantages of model predictive torque control are

- Concepts are very intuitive and easy to understand.
- The multivariable case can be easily considered.
- Easy inclusion of non-linearities in the model.
- Modulator is not required
- Greater flexibility, since Constraints can be directly included in the cost function.

PTC takes advantage of discrete nature of the power converter switching states and the control processor. The high sampling frequency required should not be problem nowadays, opening interesting possibilities with a conceptually different approach to optimization in the control of power converters and drives.

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