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Digital Simulation of Conventional Direct Torque Control of Induction Motor Drive with Reduced Flux and Torque Ripples

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Abstract

The induction motors are known as the workhorses of industry because of its simple construction and robustness. Traditionally, the induction motor has been used in constant and variable speed drive applications that do not cater for fast dynamic processes. Because of recent development of several new control technologies, such as vector control, sensor less control and direct torque control (DTC), the situation is changing rapidly. The Direct Torque Control (DTC) technique has the feature of precise and quick torque response and reduction of the complexity of field oriented control (FOC) algorithms. In DTC, the generation of inverter switching state is made to restrict the stator flux and electromagnetic torque errors with in the respective flux and torque hysteresis bands so as to obtain the fastest torque response and highest efficiency at every instant. In this paper, a detailed mathematical modeling of induction motor is proposed and then a conventional direct torque control method is implemented where the torque and flux of an induction motor can be directly and independently controlled without any co-ordinate transformation using MATLAB simulation.

Keywords: Induction motor, direct torque control, MATLAB, total harmonic distortion, voltage vector, Mathematical modeling.r

Introduction

Rotational industrial loads require operation at any one of a wide range of operating speeds. Such loads are generally termed as variable speed drives or adjustable speed drives. The variable speed drive systems are also an integral part of automation. There are three basic types of variable speed drive systems: electrical drives, hydraulic drives and finally mechanical drives [1]. AC motors exhibit highly coupled, nonlinear and multi variable structures as opposed to much simpler decoupled structures of separately excited DC motors. The AC motors have a number of advantages: light weight, inexpensive and have low maintenance compared with DC motors. They require control of frequency, voltage and current for variable speed applications. However, the advantages of AC drives outweigh the disadvantages. AC drives are replacing DC drives and are used in many domestic and industrial applications [2]. This motor is by far the most widely used motor in the industry. Traditionally, it has been used in constant and variable speed drive applications that do not cater for fast dynamic processes. Because of recent development of several new control technologies, such as vector control, sensorless control and direct torque control (DTC), the situation is changing rapidly [3]-[4]. In scalar control, the torque pulsations are present at low speeds owing to presence of fifth, seventh and eleventh and higher harmonics, Because of the presence of low frequency harmonics, the motor losses are increased at all speeds causing the derating of the motor and the harmonic content increase at low speeds, increasing the losses. The increase in the (v/f) ratio at low speeds to compensate for the stator resistance drop may cause a higher motor current to flow at light loads due to saturation [5]. These two effects may cause overheating of the machine at low speeds. The main drawbacks of vector control method are the motor is modeled in rotating reference frame, which is more sensitive to motor parameters, the torque is indirectly controlled and the inclusion of PWM modulator, which processes the voltage and frequency outputs of the vector control stage, creates a signal delay between the input reference and the resulting stator voltage vector produced [6]. To overcome these disadvantages the Direct Torque Control (DTC) principle was developed by Takahashi and Noguchi for low and medium power applications in 1980's [7]. The Direct Torque Control (DTC) uses an induction motor model to predict the voltage required to achieve a desired output torque [8]. By using only current and voltage measurements, it is possible to estimate the instantaneous stator flux and output torque. In the DTC approach, the reference torque and reference flux are compared to the estimated motor torque and the estimated stator flux respectively, both employing hysteresis controllers [9]. The torque and flux hysteresis controller output logic signals are evaluated in an optimal switching logic table to generate the inverter switching device gate signals [10]. In this paper, the Direct Torque Control method is implemented for induction motor drive to overcome the disadvantage of other control strategies. The simulation results obtained from Matlab/Simulink are presented.

Mathematical Modeling of Induction Motor

Before going to analyze the any motor or generator it is very much important to obtain the machine in terms of equivalent mathematical equations. Traditional per phase equivalent circuit has been widely used in steady state analysis and design of induction motor, but it is not appreciated to predict the dynamic performance of the motor. The dynamic model of the induction motor is derived by using a two-phase motor in direct and quadrature axes. This approach is desirable because of the conceptual simplicity obtained with two sets of windings, one on the stator and the other in the rotor. The equivalence between the three phase and two phase machine models is derived from simple observation, and this approach is suitable for extending it to model an n-phase machine by means of a two phase machine. The concept of power invariance is introduced; the power must be equal in the three-phase machine and its equivalent two-phase model. The required transformation in voltages, currents, or flux linkages is derived in a generalized way. To study the dynamic performance of the machine model, a motor model has been developed in a stationary reference frame by using equations (1)-(3).

$$\begin{aligned} v_{ds} &= R_s i_{ds} + \frac{d\lambda_{ds}}{dt} \\ v_{qs} &= R_s i_{qs} + \frac{d\lambda_{qs}}{dt} \\ 0 &= R_r i_{dr} + \omega_r \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \\ 0 &= R_r i_{qr} - \omega_r \lambda_{dr} + \frac{d\lambda_{qr}}{dt} \end{aligned} \qquad (1)$$

The stator and rotor flux linkages in the stator reference frame are defined as,

$$\begin{aligned} \lambda_{qs} &= L_s i_{qs} + L_m i_{qr} \\ \lambda_{ds} &= L_s i_{ds} + L_m i_{dr} \\ \lambda_{qr} &= L_r i_{qr} + L_m i_{qs} \\ \lambda_{dr} &= L_r i_{dr} + L_m i_{ds} \end{aligned} \qquad (2)$$

The electromagnetic torque of the induction motor in stator reference frame is given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \qquad (3)$$

By using the above equations the induction motor model is developed in stator reference frame. The simulation of induction motor has been carried out in the Matlab-Simulink environment under the no-load condition.

Principle of Conventional Direct Torque Control

The electromagnetic torque of a three-phase induction motor can be written as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}\left|\psi_r\right|\left|\psi_s\right|\sin\delta \qquad (4)$$

where δ is the angle between the stator flux linkage space vector ($\overline{\psi}_s$) and rotor flux linkage space vector ($\overline{\psi}_r$), as shown in Fig. and σ is the leakage coefficient given by

$$\sigma = 1 - \left(\frac{L_m^2}{L_s L_r}\right).$$

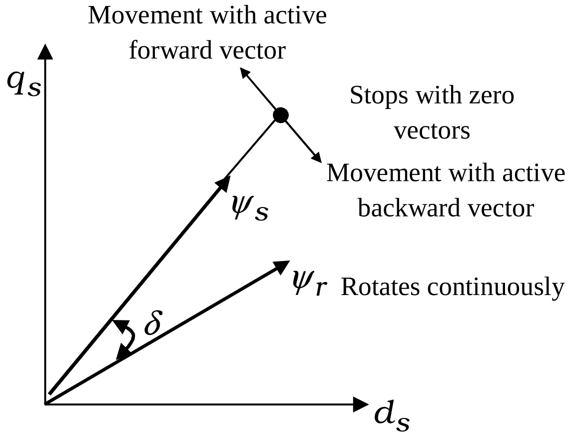

Fig.1 $\overline{\psi}_s$ movement relative to $\overline{\psi}_r$ under influence of voltage vectors

The expression given in (4) is valid for both the steady state and transient state conditions. In steady state, both the stator flux and rotor flux move with the same angular velocity. The rotor flux lags the stator flux by torque angle. But, during transient condition, these two vectors do not have the same velocity. From (1), it is clear that the motor torque can be altered by varying the rotor or stator flux linkage vectors. The magnitude of the stator flux is normally kept constant. By considering the three-phase, two-level, six pulse voltage source inverter (VSI), there are six non-zero active voltage space vectors and two zero voltage space vectors as shown in Fig.2. The six active voltage space vectors can be represented as,

$$\overline{V}_k = \frac{2}{3}V_{dc}\exp\left[j(k-1)\pi/3\right] \quad k = 1,2,\ldots,6 \qquad (5)$$

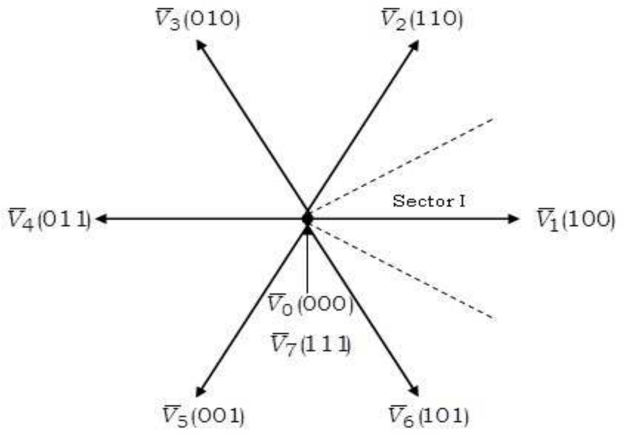

Fig. 2 Inverter voltage space vectors

Depending on the position of stator flux linkage space vector, it is possible to switch the appropriate voltage vectors to control both stator flux and torque.

Common Mode Voltages

For the most common two-level voltage source inverter there are three switching variables a, b, c one per phase of the inverter. Fig 3 shows a voltage source inverter (VSI) connected to a motor. Every terminal of the induction motor will be connected to the pole of one of the inverter legs, and thereby, either to the positive dc bus or the negative dc bus.

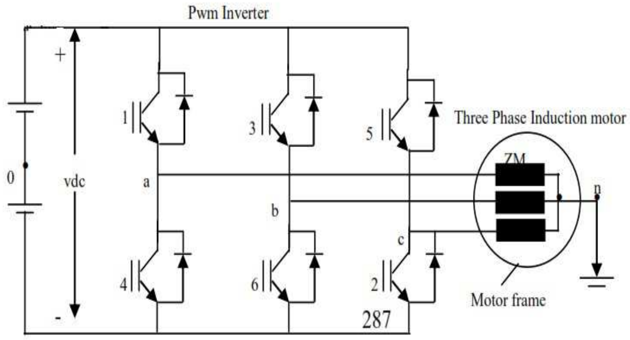

Fig.3 Voltage source inverter connected to induction motor

There are eight output voltage vectors in which six are active voltage vectors and remaining two vectors are zero voltage vectors with totally eight possible switching states of the inverter. The CMV is the potential of the star point of the load with respect to the Centre of the dc bus of the VSI. The CMV generated by a star connected three phase electric machine is given by

$$V_{com}=\frac{\left(V_{ao}+V_{bo}+V_{co}\right)}{3} \tag{6}$$

Where V_{ao}, , V_{bo} and V_{co} are the phase voltages.

Direct Torque Controlled Based Induction Motor Drive

The Fig.4 shows the block diagram of conventional direct torque controlled induction motor drive. There are two hysteresis control loops, one for the control of torque and other for the control of stator flux. The flux controller controls the machine operating flux to maintain the magnitude of the operating flux at the rated value till the rated speed. Torque control loop maintains the torque close to the torque demand. Based on the outputs of these controllers and the instantaneous position of stator flux vector, a proper voltage space vector is selected. Based on the outputs of hysteresis controllers and position of the stator flux vector, the optimum switching table will be constructed. This gives the optimum selection of the switching voltage space vectors for all the possible stator flux linkage space vector positions.

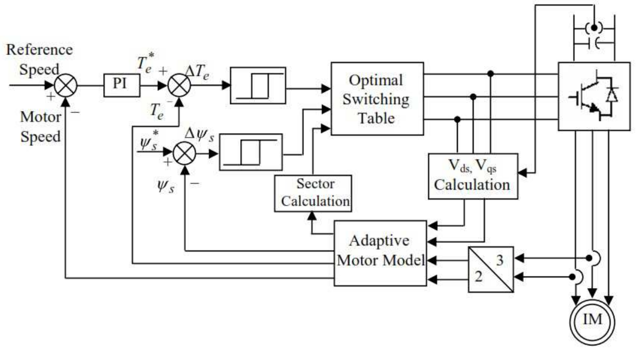

Fig.4 Block diagram of conventional DTC

In conventional DTC (CDTC), the stator flux linkage and torque errors are restricted within their respective hysteresis bands, which are $2\Delta\psi_s$ and $2\Delta T_e$ wide respectively. If a stator flux increase is require then $S_\psi = 1$; if a stator flux decrease is required then $S_\psi = 0$. The digitized output signals of the two level flux hysteresis controller are defined as,

$$\text{If } \bar{\psi}_s \le \bar{\psi}_s^* - \Delta\psi_s \text{ then } S_\psi = 1$$

$$\text{If } \bar{\psi}_s \ge \bar{\psi}_s^* + \Delta\psi_s \text{ then } S_\psi = 0$$

If a torque increase is required then $S_T = 1$, if a torque decrease is require then $S_T = -1$, and if no change in the torque is required then $S_T = 0$. The digitized output signals of the three level torque hysteresis controller for the anticlockwise rotation or forward rotation can be defined as,

$$\text{If } T_e^* - T_e \ge \Delta T_e \text{ then } S_T = 1$$

$$\text{If } T_e \ge T_e^* \text{ then } S_T = 0$$

And for clockwise rotation or backward rotation

$$\text{If } T_e^* - T_e \le -\Delta T_e \text{ then } S_T = -1$$

$$\text{If } T_e \le T_e^* \text{ then } S_T = 0$$

Depending upon the S_ψ, S_T and the position of the stator flux linkage space vector, the suitable switching voltage vector is determined from the lookup table

Simulation Results and Discussion

To validate the conventional direct torque controlled induction motor drive, a numerical simulation has been carried out by using Matlab/Simulink. The simulation parameters and specifications of induction motor 220 Volts, Delta connected, 1.5 KW, 3-Phase, 4-pole, 1200 rpm, 50 Hz, $R_{s=}$7.83Ω, $R_{r=}$7.55 Ω, $L_{m=}$ 0.4535 H, $L_{s=}$0.4751H, $L_{r=}$0.4751H, J=0.06 Kg.m^2. For the simulation, the reference flux is taken as 1wb and starting torque is limited to 15 N-m. Various conditions such as starting, steady state, step change in load, speed reversal are simulated and the results for conventional direct torque controlled induction motor drive are shown in from Fig.5 to Fig.8. From the results it can be observed that, the CDTC gives high ripples in torque, current and stator flux during steady state. The wave form of the harmonic distortion of the common mode voltage along with the total harmonic distortion (THD) value is shown in Fig.9 and Fig.10. From the results of common mode emission of conventional DTC it can be observed that the common mode voltage is very high. The locus of the stator flux at given speed is shown in Fig 11, from which it can be observed that the locus is almost is a circle of constant radius. The harmonic spectra of line current for conventional DTC based induction motor drive is shown in Fig.12 is also reduced.

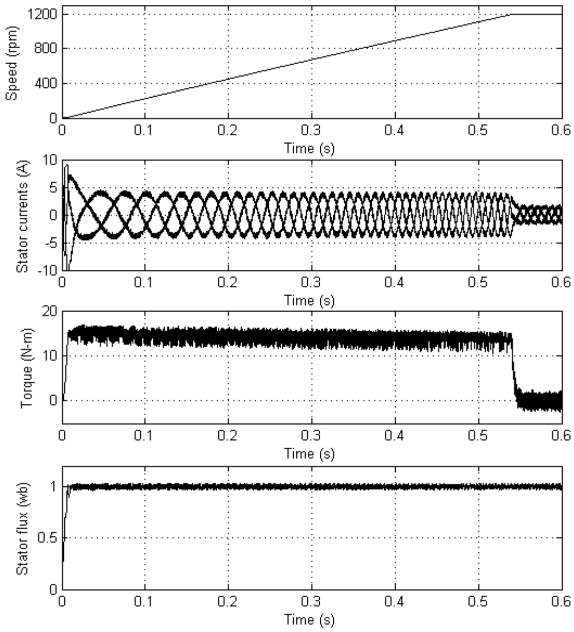

Fig.5 starting transients in conventional DTC based induction motor drive

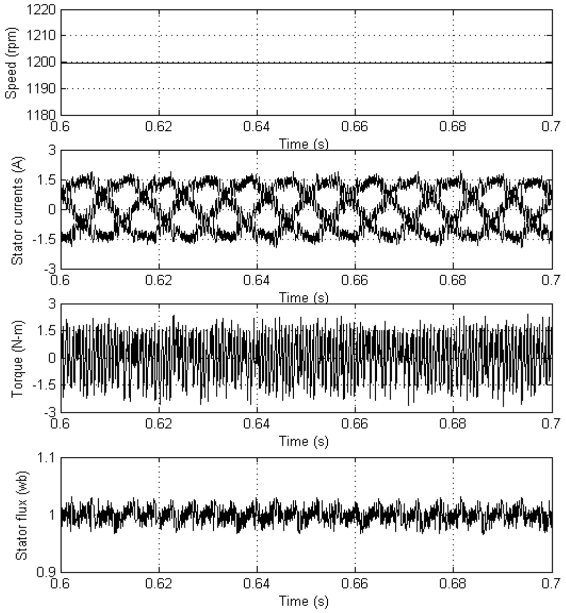

Fig.6 steady state plots for conventional DTC based induction motor drive

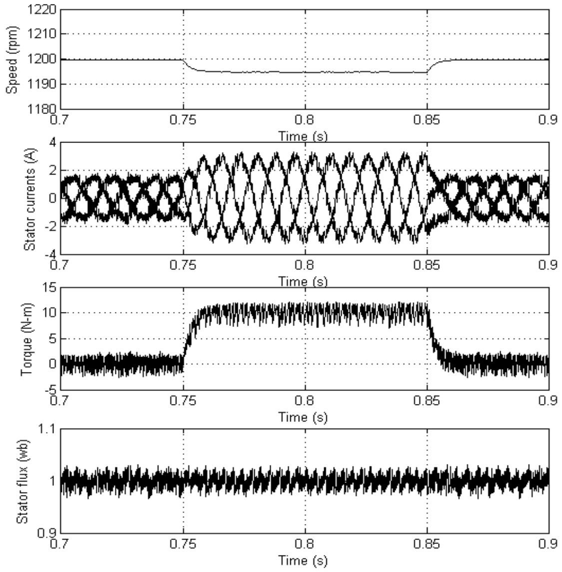

Fig.7 transients in speed, current, torque and flux during step change in load torque (a load torque of 10 N-m is applied at 0.75s and removed at 0.85s) for conventional DTC based induction motor drive

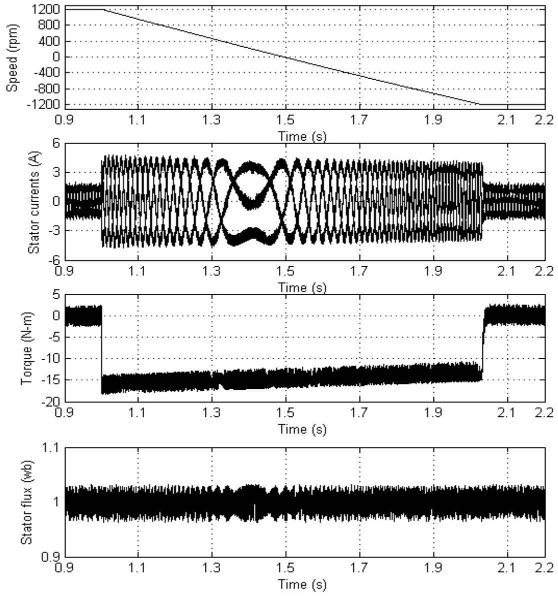

Fig.8 transients in speed, current, torque and flux during speed reversal (the speed is reversed from +1200 rpm to -1200 rpm)

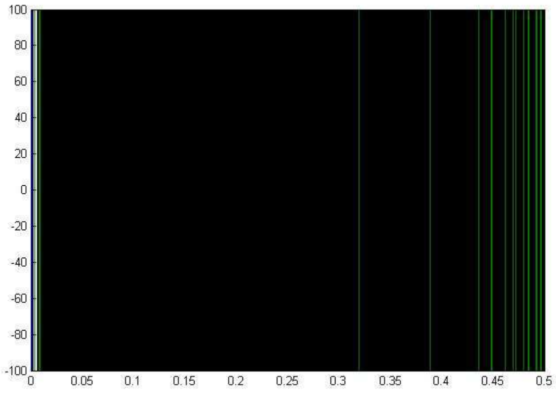

Fig.9 common mode voltage of conventional DTC based induction motor drive

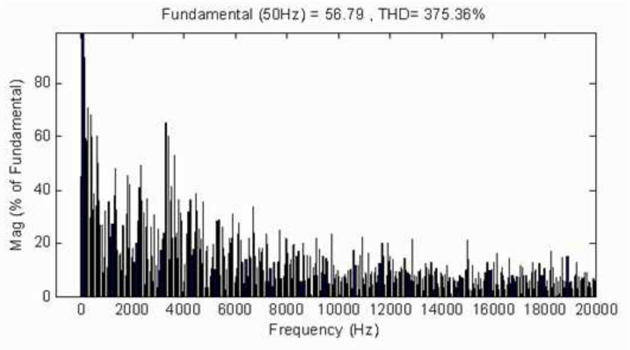

Fig.10 harmonic spectra of common mode voltage

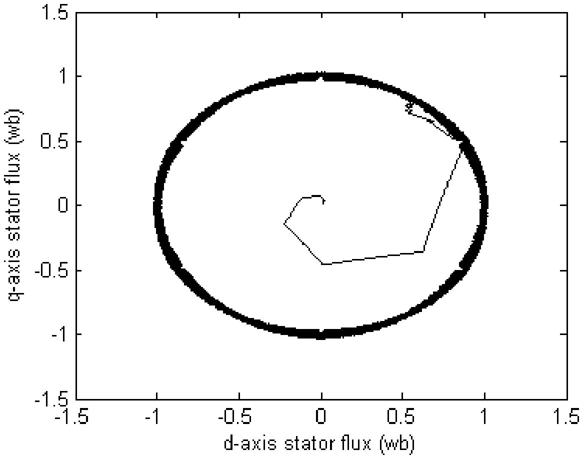

Fig.11 trajectory of stator flux for conventional DTC based induction motor drive

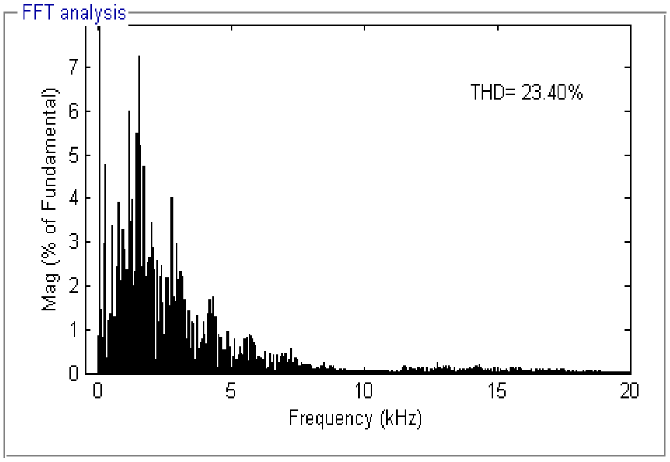

Fig.12 harmonic spectra of line current for conventional DTC based induction motor drive

Conclusion

In this paper, the dynamic behavior of the induction motor under both transient and steady state conditions, an accurate mathematical model of the induction motor has been developed in the stationary reference frame. The stationary reference frame is simple in compared to the synchronously rotating reference frame and is used in direct torque controlled induction motor drives. As the name suggests, DTC controls the motor torque and flux directly. The DTC is simple and gives fast dynamic response. In spite of its simplicity, it gives additional steady state ripple in torque, flux and current. From the simulation results the same can be concluded.

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