Improved Performance of Direct Torque Control with PMSM compared to DTC with Induction Motor

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Abstract: For induction motor torque control, direct torque control is becoming the industry standard. This paper proposes a switching loss minimization technique for improved Direct Torque Control (DTC) of permanent magnet synchronous motors in order to increase the drive system's steady-state and dynamic results. Direct torque control (DTC) of a voltage source inverter-supplied PMSM is a simple scheme that requires little computation time, can be implemented without speed sensors, and is unaffected by parameter variations. In theory, the motor terminal voltages and currents are used to calculate the flux and torque of the motor. A voltage vector is chosen to restrict the flux and torque errors within their flux and torque hysteresis bands based on the instantaneous torque and stator flux magnitude errors, as well as estimates of the flux position. The electromagnetic torque, rotor speed, and stator current of DTC with PMSM and DTC with IM were successfully calculated using Total Harmonic Distortion (THD) in this article. As compared to DTC with IM, DTC with PMSM reduced THD by 12 percent in torque, speed, and stator current [21]. Switching Losses Minimization Technique by THD Minimization is used in this article. Since transistors are only switched when necessary to maintain torque and flux within their hysteresis limits, switching losses are minimised, resulting in increased efficiency and lower losses. Matlab SIMULINK has experimentally confirmed direct torque regulation with PMSM and IM.

Keywords: Direct torque control, PMSM, induction motor, torque ripple minimization

1. Introduction

In the area of AC drives for induction motors, Direct Torque Control (DTC) has been extensively studied over the last decade. Takahashi [1] first proposed this control technique in 1986, and Depenbrock [4] developed it in 1988. Despite this, only one major manufacturer has a DTC-based industrial application, which was launched in 1995 [5]. The key benefit of DTC is the high performance (decoupled control stator flux and torque, quick torque response, and robustness) obtained, as well as the scheme's simplicity (coordinate transformation, modulation block and current regulation block not require). The traditional voltage source inverter (VSI) used in AC drives has two switches per leg, with the load connected to either the upper or lower line of the DC-link. This is referred to as a two-level VSI. However, the maximum voltage that can be handled by quick semiconductors is limited. For high power and voltage applications, a series link is needed, which necessitates a voltage balance. Furthermore, the dV/dt is extremely high, resulting in significant electromagnetic interference (EMI) and high winding insulation tension. Multilevel inverters are a new form of inverter that can resolve the drawbacks of the traditional low-cost two-level VSI [5]. Over the last decade, DTC drive has emerged as a viable alternative to the well-known Vector Control of Induction Machines. Its key feature is that it provides good performance, with results that are as accurate as classical but with many advantages due to its simpler control diagram. As the name implies, DTC (Direct Torque Control) is characterised by directly controlled flux and torque, implying indirectly controlled stator voltage and current. In contrast to traditional vector-controlled drives, the DTC has some benefits, such as approximately sinusoidal stator currents and fluxes. High dynamic efficiency, even when the rotor is locked and at a standstill Absences of mechanical transducers, absences of coordinates turn There are no current regulators, PWM pulse generation, PI flux and torque control, or coordinate transformation needed, Reduced parameter sensitivity, superior dynamic properties, and a simple control scheme with a short computation time. Traditional DTC has some drawbacks, such as potential issues during startup and low-speed service, and variable switching frequency; these are drawbacks that we want to avoid by combining DTC with PMSM. We'll go into how DTC regulation is used in PMSM in the following parts.[3][6][9].

This paper proposes two separate control methods. The first is focused on a two-level inverter adaptation of the standard DTC scheme. The second is built on a Fuzzy Logic Controller, which is used to replace the DTC's traditional table for inverter state selection. Takahashi [3] and Depenbrock created a direct torque control (DTC), which is a simpler variant of field orientation [4]. A DTC for an induction motor is shown in Fig.1. It is possible to monitor the stator flux linkage and electromagnetic torque directly in DTC drives by selecting an optimal inverter switching state. Switching state is used to keep flux and torque errors within their hysteresis bands, allowing for the quickest torque response and maximum efficiency at all times. DTC is less dependent on the motor model than field-oriented control since the stator resistance value is the only system parameter used to measure the stator flux. One of the drawbacks of DTC mentioned in [7] is high torque ripple. An active switching state causes the torque to increase past its reference value until the end of the switching cycle under constant load in steady state; then a zero voltage vector is applied for the next switching period, causing the torque to decrease below its reference value until the end of the switching period. Using a high switching frequency to minimise torque ripple is one option; however, this necessitates the purchase of expensive processors and switching devices. The use of a fuzzy logic duty ratio controller is a less costly option. In DTC with duty ratio power, rather than applying the selected voltage vector for the entire switching period as in conventional DTC, the selected voltage vector is applied for a portion of the switching period.

The efficient switching frequency is doubled for the rest of the zero voltage vector era by adding a nonzero voltage vector for just a portion of the switching period. As a result, for any single switching time, the torque differences between below and above the average value are smaller. The average stator voltage is also changed directly since the duty ratio is regulated. There is no need to use several switching cycles with a nonzero voltage vector or a single switching period with a zero voltage vector to allow course corrections. The total torque ripple is minimised, and the average phase voltage is balanced more smoothly. In this paper, the THD calculation was completed successfully. As compared to DTC with IM, DTC with PMSM reduced THD by 12 percent in torque, rpm, and stator current [21]. Via THD minimization, hear switching loses the minimization strategy. Since the transistors are only switched when necessary to maintain torque and flux within their hysteresis limits, switching errors are decreased, resulting in improved performance and lower losses. In [14], the use of a PMSM in DTC is suggested. The aim of this paper is to show that a DTC with a PMSM decreases torque ripple as compared to a traditional DTC by simulation and experimentation.

2. DTC Schematic

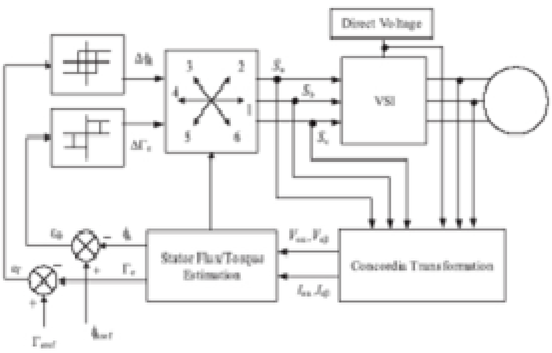


Fig.1. Block diagram of DTC scheme

Flux	Torque	Sector Sφ					
Δφ	Δτ	Sφ1	Sφ2	Sφ3	Sφ4	Sφ5	Sφ6
1	1	V2	V3	V4	V5	V6	V1
1	0	V7	V0	V7	V0	V7	V0
1	-1	V6	V1	V2	V3	V4	V5
-1	1	V3	V4	V5	V6	V1	V2
-1	0	V0	V7	V0	V7	V0	V7
-1	-1	V5	V6	V1	V2	V3	V4

Table 1. Classical DTC switching table

In the DTC scheme seen in Figure 1, the and signals are sent to two hysteresis comparators. Changes in magnetic flux, mechanical torque, and stator flux location sectors are the digitised output variables. SN produced a digital word that selects the appropriate voltage vector from Table 1's switching. To monitor the power switches in the inverter, the collection produces pulses Sa, Sb, and Sc. According to the torque controller's outputs, three-level torque and two-level flux hysteresis controls are used, and sector information of appropriate voltage vectors for both inverters is picked from a switching table, as shown in fig.2 [2]. When the stator flux vector is lying in sector I, as seen in fig.3, the voltage vectors that normally participate in DTC scheme are seen in fig.2. The torque and stator flux are held within the limits of two hysteresis bands by selecting a voltage vector at each cycle time. Although a fast torque response can be obtained, the steady state output results in undesirable ripples in current, flux, and torque, owing to the voltage selection algorithm's lack of knowledge about torque and rotor speed values [10] [17].

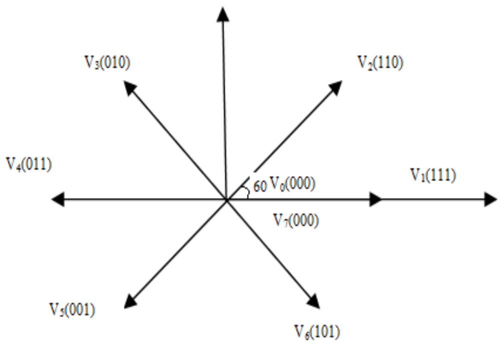


Fig.2. Eight possible voltage space vectors

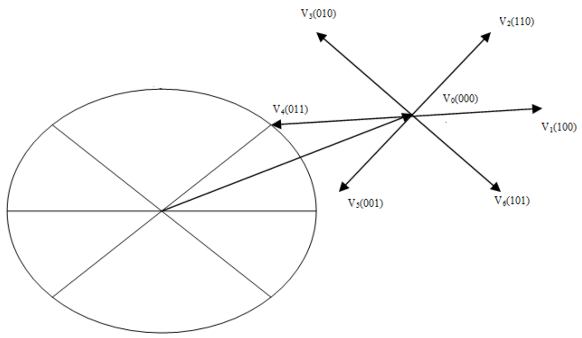


Fig.3. Stator flux vector

3. Modeling Of Pmsm For DTC

The mathematical model for the vector control of the PMSM has been derived for its dynamic d-q model using the model of the synchronous machine without damper winding and field current dynamics. The stator winding volumes are converted to the synchronous rotating reference frame that rotates at rotor speed using the synchronously rotating rotor reference frame. In the rotor reference frame, a model of PMSM without damper winding was constructed using assumptions such as Saturation is ignored, induced EMF is sinusoidal, core losses are marginal, and there are no field current dynamics. It's also worth noting that at any given operating stage, rotor flux is constant and localised along the d-axis, with zero flux along the q-axis, a similar assumption made in the development of indirect vector driven induction motor drives. When the orientation of the rotor magnets is taken into account, the instantaneous induced emf and, as a result, the stator currents and torque of the system can be determined independently of the stator voltages and currents using a rotor reference frame. When a rotor reference frame is considered, it means that the corresponding q- and d-axis stator windings are converted into rotor-speed reference frames. The rotor and stator magnetic fields have a zero speed difference, and the stator q- and d-axis windings have a fixed phase interaction with the rotor magnet axis, which is the d-axis in the modelling [17,18].

The mathematical model of a PMSM given by complex equations in the rotor reference frame is as below:

Voltage equations are given by:

$$V_d = R_s i_d - \omega_r \lambda_q + \frac{d\lambda_d}{dt} \ldots .1, \qquad V_q = R_s i_q - \omega_r \lambda_d + \frac{d\lambda_q}{dt} \ldots .2$$

Flux linkage is given by

$$\lambda_q = L_q i_q \qquad \ldots \ldots \ldots 3, \qquad \lambda_d = L_d i_d + \lambda_f \ldots \ldots \ldots \ldots \ldots \ldots 4$$

Substituting Equation 3 and 4 in 1 and 2, we get,

$$V_q = R_s i_q - \omega_r \left(L_d i_d + \lambda_f\right) + \frac{d(L_q i_q)}{dt} \ldots 5, \quad V_d = R_s i_d - \omega_r L_q i_q . + \frac{d}{dt}\left(L_d i_d + \lambda_f\right) \ldots ..6$$

Arranging equation 5 and 6 in matrix form,

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \frac{dL_q}{dt} & \omega_r L_d \\ -\omega_r L_q & R_s + \frac{dL_d}{dt} \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \frac{d\lambda_f}{dt} \end{pmatrix} \ldots \ldots 7$$

The developed motor torque is being given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right) \ldots \ldots 8, \qquad T_e = \frac{3}{4} P\left[\lambda_f i_q + \left(L_d - L_q\right) i_q i_d\right] \ldots \ldots 9,$$

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \ldots \ldots .10$$

Solving for rotor mechanical speed from equation 10, we get,

$$\omega_m = \int \left(\frac{T_e - T_L - B\omega_m}{J}\right) dt \ldots \ldots 11$$

And rotor electrical speed is

$$\omega_r = \omega_m \left(\frac{P}{2}\right) \ldots \ldots \ldots \ldots \ldots \ldots ..12$$

4. DTC Controller

The requisite stator flux is imposed using the state of the Voltage Source Inverter. By ignoring the ohmic decreases, the stator voltage specifically influences the stator flux in line with the following equation:

$\frac{d}{dt}\bar{\psi}_s = \bar{u}_s \ldots\ldots\ldots\ldots(9)$ Or $\overline{\Delta\psi_s} = \bar{u}_s \Delta t \ldots\ldots\ldots(10)$

Where $\frac{d}{dt}\bar{\psi}_s$ represents the change in stator flux caused by the application of an inverter V_s

The radial and tangential components of the stator flux-linkage space vector, respectively, have decoupled power of the stator flux modulus and torque. In the same directions, these two components are exactly proportional to the components of the respective voltage space vector. The hysteresis band must be wide enough to keep the inverter switching frequency below a certain threshold, which is normally determined by control unit thermal constraint. Since the hysteresis bands are set to handle the worst locus case, the system's output will eventually suffer in a certain operating range, especially at low speeds. In torque hysteresis controller, an elapsing time to move from lower to upper limit, and vice versa can be changed according to operating condition [4,5,6].

A. Switching Losses

Switching losses (which occur when systems are turned on or off) and conduction losses are the two types of losses that occur in semiconductors (due to the ohmic resistance). The applied voltage, commutated current, and semiconductor characteristics all influence these losses. The Ideal switch turn-on (energy) loss is calculated by observing that the voltage seen by each semiconductor in a VSI inverter is always half the total DC-link voltage.

$E_{on} = e_{on}\frac{1}{2}V_{dc}i_{ph}$..........(10)

The step current is iph, and aeon is a coefficient. A corresponding equation with the coefficient eoff is found for the Ideal transition, turn-off losses. eoff is typically a factor of ten times greater than aeon. The switch-on losses of a diode are essentially negligible. However, the reverse recovery losses, or turn-off losses, are linear in voltage but nonlinear in the commutated phase current. Conduction losses, including switching losses, are affected by the applied voltage and phase current. Facing variations in the neutral point, the DC connection voltage remains stable. The phase current is the amount of the current ripple and the fundamental component, which is only affected by the operating point, which is determined by torque and rpm, but not by the switching pattern. The conduction losses can be considered independent of the switching pattern since the ripple is minimal relative to the fundamental current (typically in the region of 10% for a 3-level inverter).

5. Simulation Results

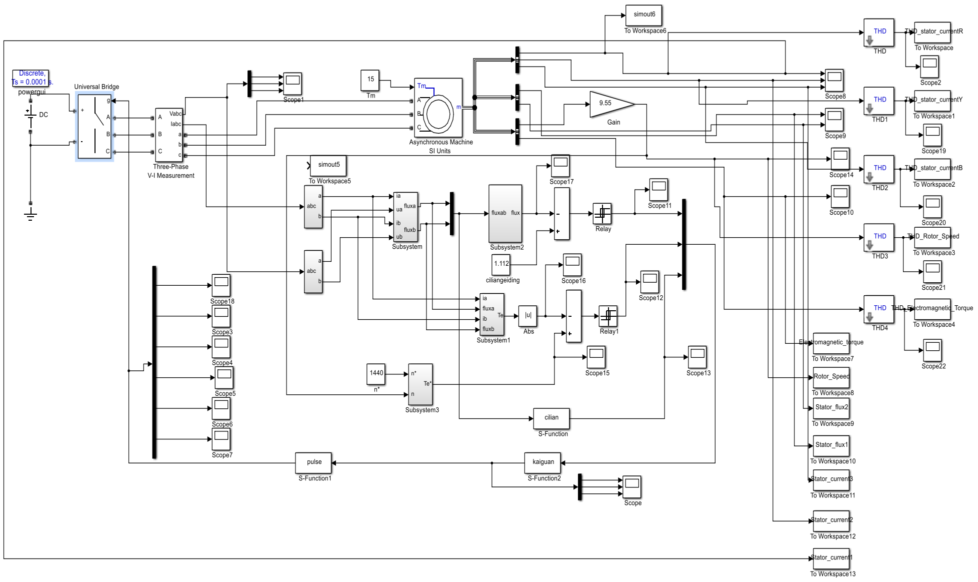
A 4-pole induction machine was replicated and compared using traditional DTC and DTC with PMSM. For DTC with IM, 15 Nm and 0.9 Wb constant torque and flux commands were used. Both simulations will use the following motor characteristics: Table II shows the parameters of the PMSM engine. Both simulations will use the following motor characteristics:

Stator phase resistance Rs (ohm)		= 4.3
Armature Inductance	(H)	= 0.0001
Flux linkage established by magnets	(V.s)	= 0.05
Voltage Constant	(V_peak L-L / krpm)	= 18.138
Torque Constant	(N.m / A_peak)	=0.15
Inertia, friction factor, pole pairs	[J (kg.m^2)]	=0.000183
Friction factor	F (N.m.s)	= 0.001
Pole pairs	p()	=2
Initial conditions	[wm(rad/s) thetam(deg) ia,ib(A)]	= [0,0, 0,0]
Sampling Time	(Sec)	=1

Table. 2: PMSM parameters

The DTC controller that selects the switching vector and determines the flux sector was simulated using a Matlab code file. Figures 4(a) and 4(b) demonstrate the Simulink models with traditional direct torque control for induction motors and DTC with PMSM (b). Figures 5 (a) and 6 (a) depict the motor's torque response by using traditional DTC with IM and DTC with the PMSM, respectively for a step torque command of 15 Nm with the drive output updated at a rate of 1 kHz.

In both regulators, the torque exceeds its steady state value in less than 20 milliseconds. Figures 7.(a) and 7.(b) display the torque characteristics in DTC with IM and DTC with PMSM, respectively (c). The stator current Ir, Iy, and Ib of the motor are seen in Fig.5(c),(d),(e) and Fig.6(c),(d),(e) using traditional DTC and DTC with PMSM, respectively. When the DTC with PMSM is used, the stator current ripple is reduced. DTC with IM also reduces torque and flux ripples, and it improves DTC efficiency, particularly at low speeds, as seen in the graph below compared to [21]. The use of a predictive torque control system with a multilevel inverter has the potential to increase efficiency in the future. We might expect the PCC algorithm to significantly reduce calculation time if a



multilevel inverter is used.

Fig.4 (a) Matlab, Simulink model of Direct Torque Control of Induction Motor

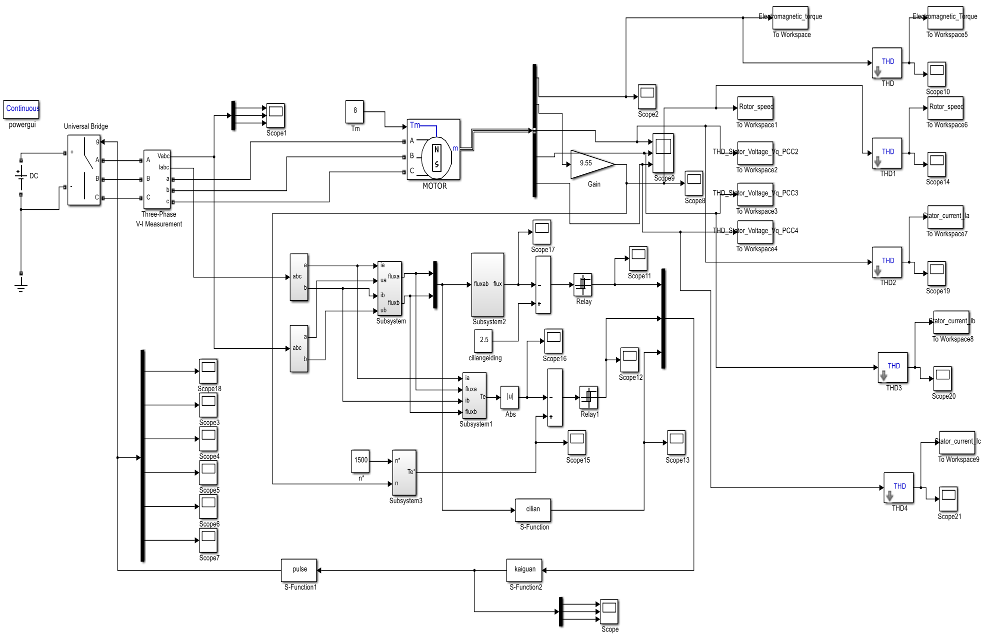


Fig.4 (b) Matlab, Simulink model of Direct Torque Control of PMSM

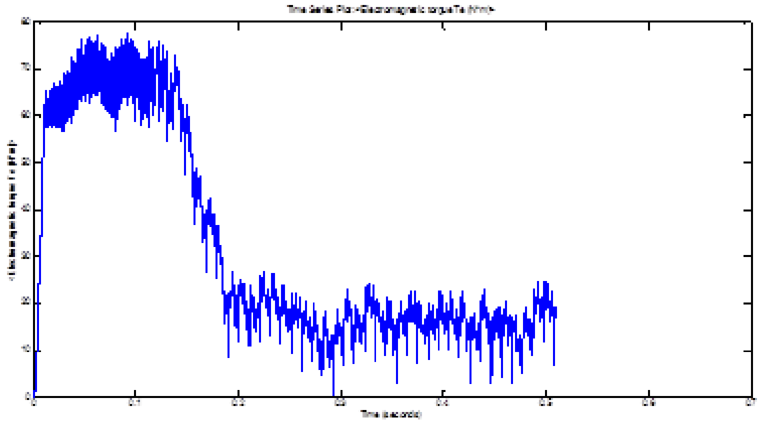


Fig.5.(a) Electromagnetic torque in DTC IM

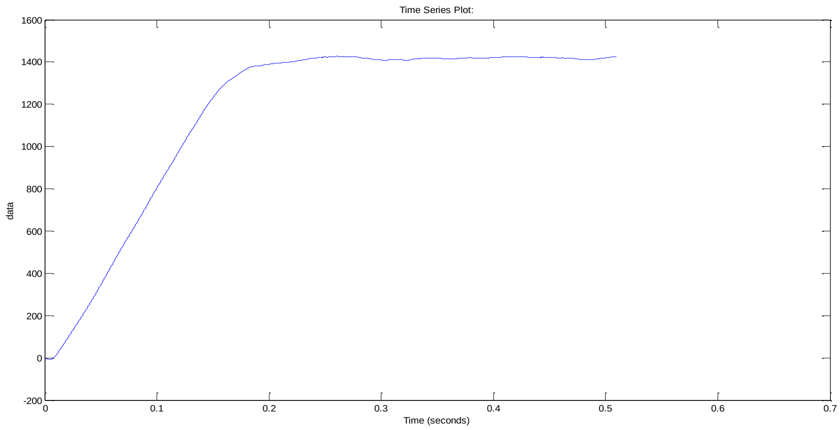


Fig.5.(b) Rotor speed in DTC IM

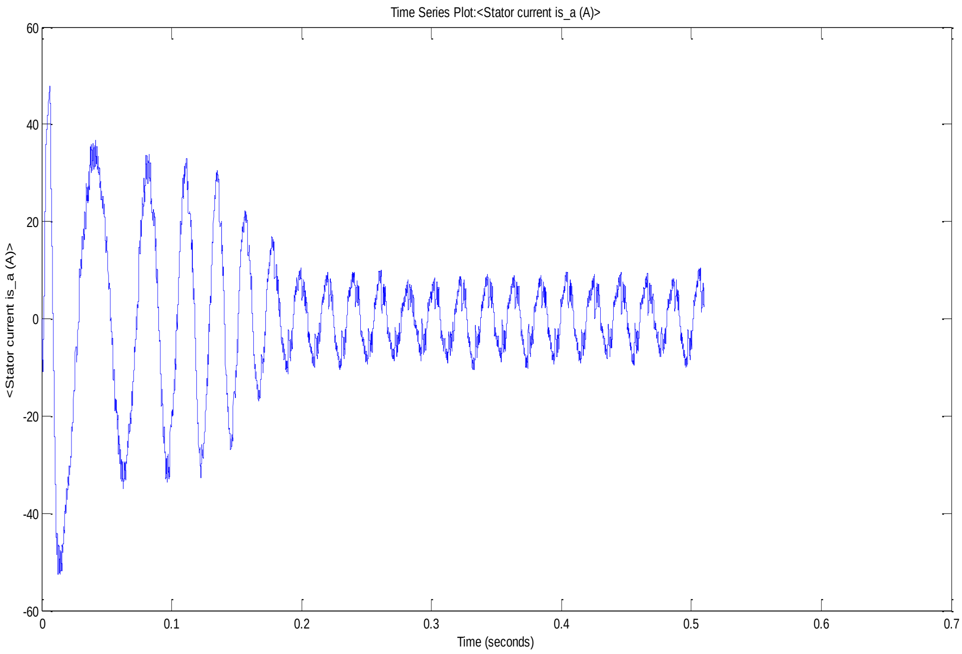


Fig.5.(c) I_R in DTC

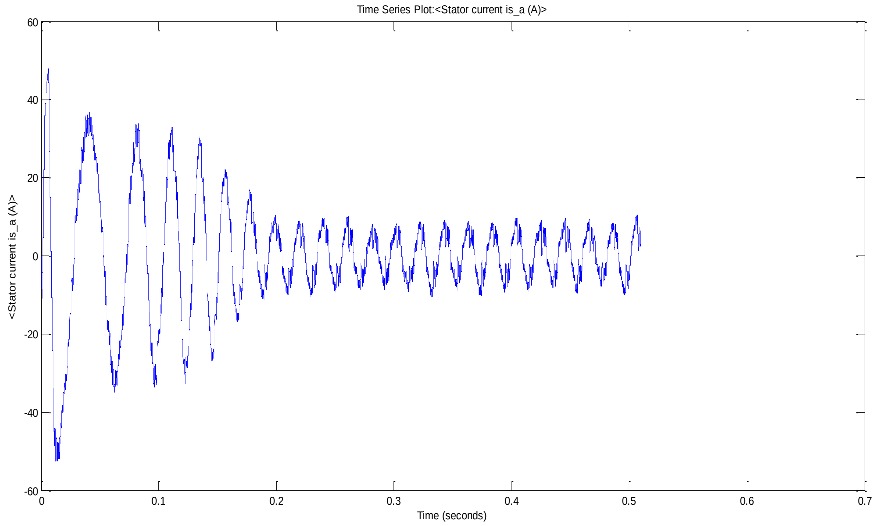


Fig.5.(d) I_Y in DTC

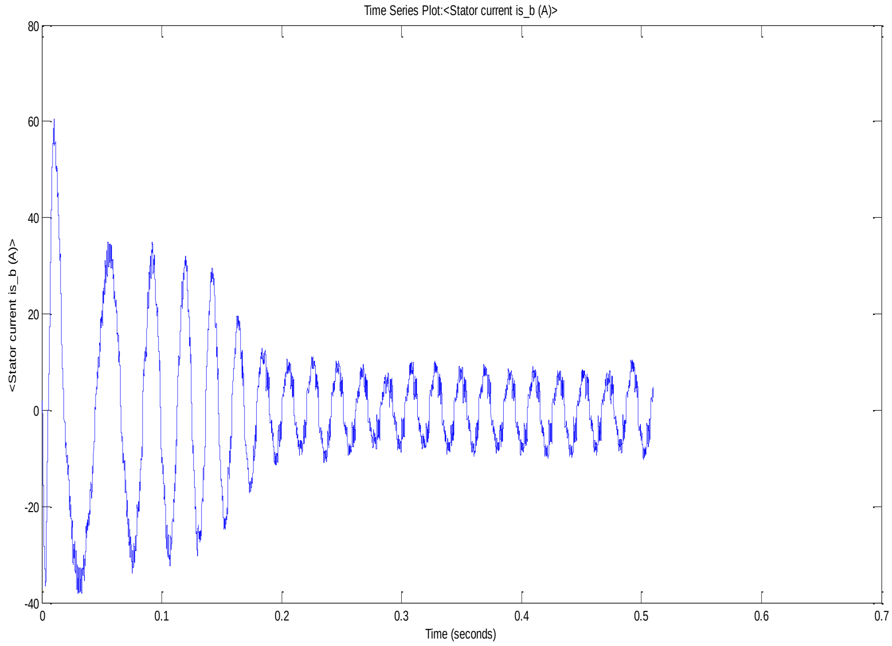


Fig.5.(e) I_B in DTC

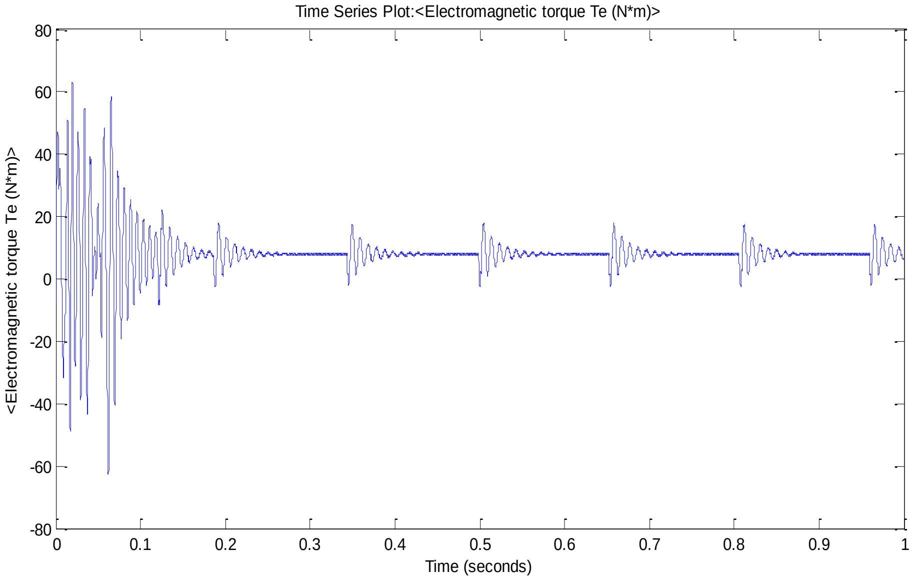


Fig.6.(a) Electromagnetic torque in DTC PMSM

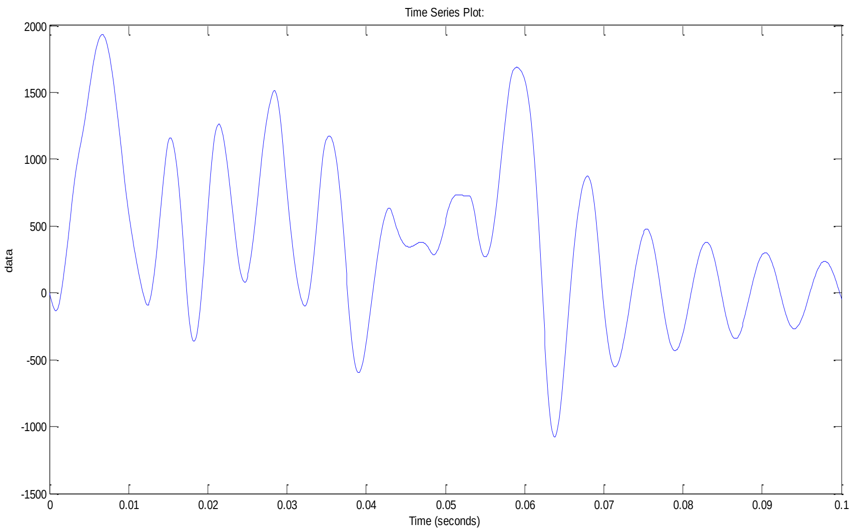


Fig.6.(b) Rotor speed in DTC PMSM

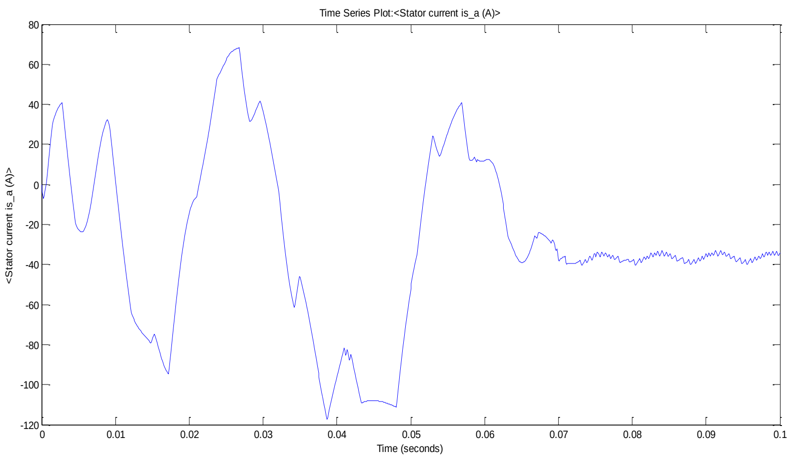


Fig.6.(c) I_R in DTC with PMSM

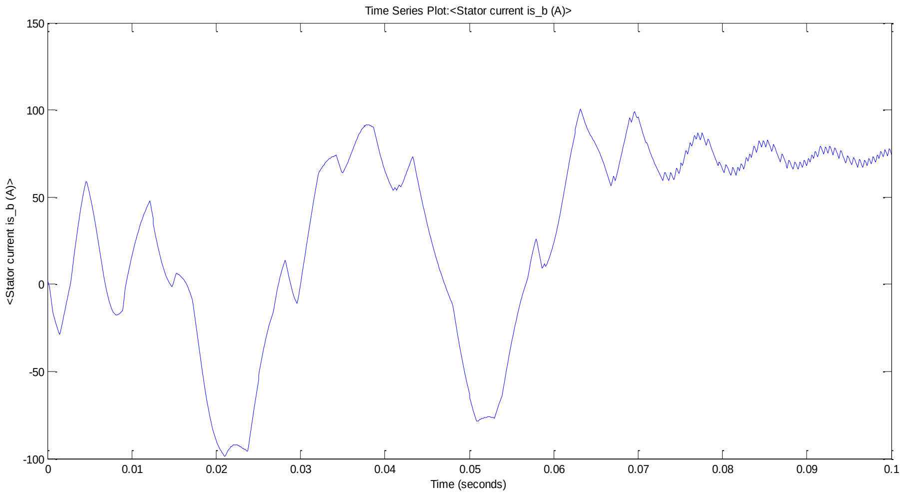


Fig.6.(d) I_Y in DTC with fuzzy

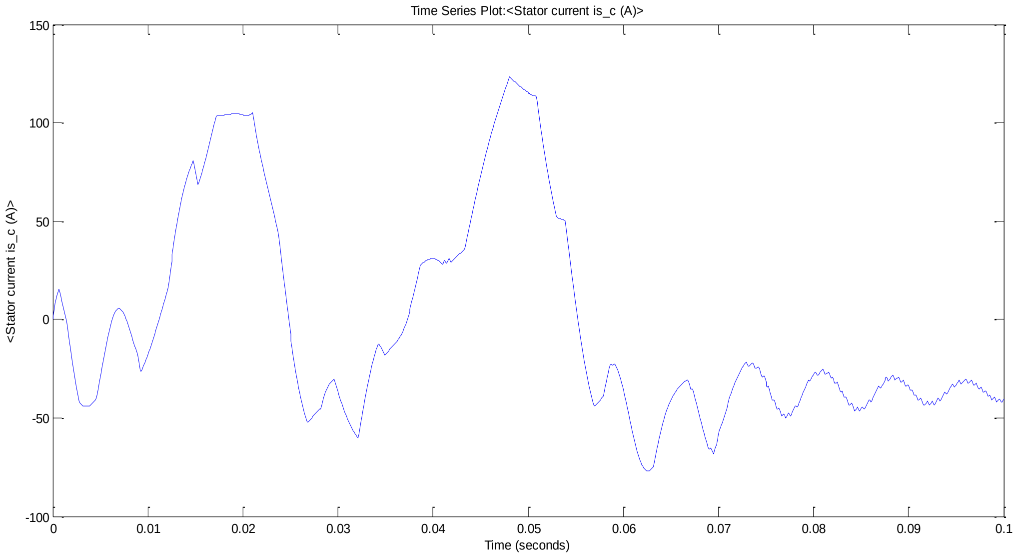
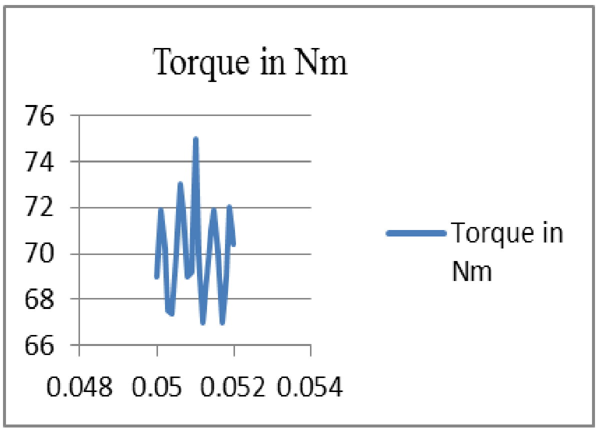


Fig.6.(e) I_B in DTC with fuzzy

Case study:



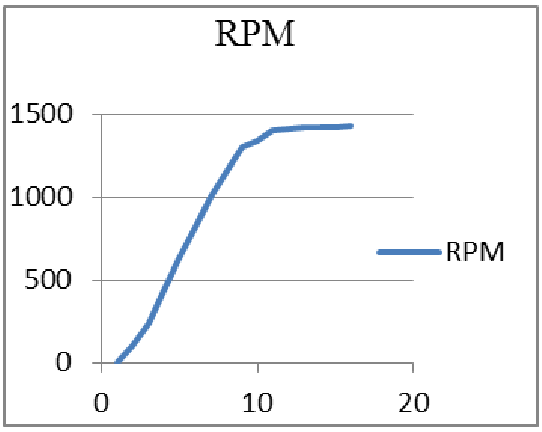


Fig.7 (a) Torque in DTC model **Fig.7 (b)** Speed in DTC model

Fig.12 Case Study of Speed and Torque in DTC and DTC with Fuzzy

c) %THD Calculation in DTC and in DTC fuzzy logic controller :

Type	**Torque(%THD)**	**Speed(%THD)**	**Stator Current R-ph(%THD)**	**Stator Current Y-ph(%THD)**	**Stator Current B-ph(%THD)**
DTC IM	62.28%	88.47%	86.52%	62.39%	60.82%
DTC PMSM	51.01%	76.40%	79.86%	50.29%	51.55%

Table.2 %THD Calculation in DTC IM and in DTC PMS

In terms of ripple in rpm, torque, and stator current under transient situations, the proposed scheme outperforms the traditional one. The torque and speed responses of the two DTC systems are seen in Figures 7 (a) and 7 (b). In the steady state, the torque ripple in the traditional scheme is roughly 6 Nm, while it is just 4 Nm in the proposed scheme, demonstrating the dominance of the proposed DTC scheme over the conventional one [21]. In this paper, total harmonic distortion (THD) was measured successfully using MATLAB 2013 in comparison to (21). As compared to DTC seen in Table. 2 compared to [21], 12 percent THD in torque, rpm, and stator current has been reduced with the aid of DTC with PMSM.

6. Conclusion:

In this article, a novel DTC scheme for PMSM drive is introduced. Direct Torque Control (DTC) is a basic and refined induction motor drive control concept in which inverter switching influences the flux and torque of the motor directly. It can be applied without the use of speed or flux sensors, which saves money and eliminates the need for routine maintenance. It does not necessitate any coordinate transformations, which will add to the computational complexity. Another benefit of DTC over field-oriented control is that it is less vulnerable to parameter value fluctuations since it is based solely on the value of the stator resistance. The motor currents and voltages are the calculated input values for the DTC power. Without the use of sensors, the voltages can be determined from the DC-bus voltage and the inverter transition locations. The flux and torque estimator uses the voltage and current signals to calculate the stator flux and torque at a given switching time. Motor torque and flux hysteresis comparators equate current torque and flux values with reference values. Without the use of metres, the voltages can be calculated from the DC-bus voltage and inverter transition locations. The flux and torque estimator takes the voltage and current signals as inputs and outputs the stator flux and torque values for a given switching time. Hysteresis comparators for motor torque and flux equate current torque and flux values to reference values. The key cause of torque ripple in traditional DTC is that the chosen voltage vector is used in the switching cycle, regardless of the extent of the torque error, resulting in a large torque hysteresis band. Depending on the degree of the torque error and the direction of the stator flux, improved drive output can be obtained by adjusting the time of applying the chosen voltage vector at each switching cycle, resulting in a limited torque hysteresis band and hence less torque ripple. This paper proposed a DTC scheme for inverter-fed machines using PMSM. MATLAB SIMULINK was then used to simulate the effect of the parameters of PMSM on the performance of the DTC scheme and compare it to the conventional DTC with IM.

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