Sensorless Permanent Magnet Synchronous Motors (PMSM) For Torque Ripple Reduction

Jyothi Mangaveni Chitta and Srinivasa Rao Maturu

***Abstract*- Permanent Magnet Synchronous Motors (PMSM) are widely used in high-performance drives, ranging from servos to traction application. The paper presents a discrete space vector pulse-width modulation applied to DTC of PMSM, which is a compromise between performance and low complexity because the use of look-up tables. DSVM is able to produce more voltage vectors than are available with the classical DTC, by using different look-up tables depending on them value of the emf voltage induced in the stator windings, DSVM is able to produce more voltage vectors than are available with the classical DTC, by using different look-up tables depending on the value of the emf voltage induced in the stator windings, PWM and PI current regulators that Field Oriented Control (FOC) needs, Reduction of the ripple torque could be obtained by calculation of the stator flux vector variation required to exactly compensate the flux and torque errors Although this technique can clearly reduce the torque and flux ripples, more than six vectors directions are necessary to achieve a decoupled control of flux and torque of the Machine. This paper also presents the control of an PMSM through sensorless vector control using pi controller Performance of the proposed strategy is verified by simulation using MATLAB.**

***Index Terms*— PMSM,**

I. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSM) are widely used in high-performance drives, ranging from servos to traction applications. This extensive use is partly due to the important increase in energy density, mainly because of the development of high – coercive permanent magnet materials at lower cost, like Neodymium Iron Boron (NdFeB). Other advantages recognized in PMSM are high efficiency and reliance, and good dynamic performance with high torque/inertia ratio. Together with a suitable control, the PMSM has the potential of replacing the induction motor in a number of industrial, commercial and domestic applications of variable speed drives. Direct Torque Control (DTC) was introduced in 1984 by Takahashi *et al*. [1] as a new approach for torque and flux control of the Induction Machine (IM). The right selection of the vector voltages allows a decoupled control of flux and torque, without the *d-q* coordinate transformation, PWM and PI current regulators that Field Oriented Control (FOC) needs. DTC offers advantages such as lower parameter dependency and complexity compared with the FOC, which makes the system more robust and easier to Implement. Although, some drawbacks have been also stated in the literature. Among them are:

Jyothi Mangaveni Chitta is a M.Tech Student and Srinivasa Rao Maturu is working as Associate Professor, both are with Department of Electrical and Electronics Engineering, Dadi Institute of Engineering and Technology, Anakapalle, Visakhapatnam, Andhra Pradesh, India

- Difficult to control flux and torque at low speed, - Current and torque distortion during the change of the sector in α- β plane,- Variable switching frequency and also a high sampling frequency needed for digital implementation of hysteresis controllers.

However, the major DTC system drawback is its relatively high torque ripple. A low torque ripple is desirable because the torque ripple generates noise and vibrations, causes errors in sensorless motor drives, and associated current ripples are in turn responsible for the EMI. Basically, the high current and torque ripple in DTC are due to the presence of hysteresis comparators together the limited number of available voltage vectors. Since the introduction of the DTC, research has been done to solve these problems, and specially the torque ripple [2].

Reduction of the ripple torque could be obtained by calculation of the stator flux vector variation required to exactly compensate the flux and torque errors. Moreover, the control system should be able to generate any voltage vector, which implies the use of Space Vector Pulse Modulation (SVPM) [3], and complicates the control scheme. An approximation to this ideal behavior can be achieved by using a higher number of voltage vectors than those used in classical DCT. On this way, in [4] the number of available vectors is increased by using a three-level inverter. Another alternative to increase the number of available vectors is an on-line modulation between active and null vectors, in order to obtain a theoretically infinite number of applicable vectors in every six spatial directions originated by the power inverter [5].

Although this technique can clearly reduce the torque and flux ripples, more than six vectors directions are necessary to achieve a decoupled control of flux and torque of the machine. For example, in [6] the simple switching table is replaced by several switching tables, obtaining a combination of three voltage vectors into the same sampling period, which is called discrete space vector modulation (DSVM) in the paper.

In the late 1990's, DTC for the PMSM have been presented [7], with the same advantages as for IM. However, new problems appear regarding application of zero vectors. In an IM, the stator flux linkage is uniquely determined by the stator voltage. Therefore, zero voltage vectors can be applied to help to reduce flux and torque ripple. On the contrary, the stator flux linkage in a PMSM will change even when the zero voltages vectors are applied, because the magnets move with the rotor. Then, indefinite control on the flux is obtained if zero voltage vectors are used, andconsequently they should not be used in DTC for the PMSM. This is especially true at a low speed, when the zero voltage vectors application on the PMSM holds the torque rather than decreases it. As well as improving dynamics, deletion of zero vectors also causes more magnificent torque and flux ripple in steady state, and complicates the control of the motor smoothly in the low speed range. Therefore, the way of minimizing torque ripple becomes the main research subject in a DTC of PMSM.

Some papers on the DTC in PMSM's have appeared in recent years, presenting similar techniques to reduce the torque ripple than those used in IM, mainly by means of a constant inverter switching frequency by using SVPM [8]. However, the application of SVM signal generator makes the control structure of the modified DTC system more complicated and worsens the dynamic response of the drive by introducing undesirable delays. An approximation to SPVM in a DTC of PMSM is presented in [9], but only active vectors are used, and variable switching frequency is obtained. In this paper the DSVM technique is used to solve the torque ripple problem in a PMSM controlled by a DTC. DSVM divide each sample period in three equal time intervals. The system is therefore able to generate a higher number of voltage space vectors and the switching frequency is constant. Together with a 5- level torque hysteresis comparator and a more precise switch table that also depends on the level of the back-emf, the torque ripple is decreased.

II. CONTROL SCHEMES FOR PMSM MOTORS

PMSM control techniques can be divided into scalar and vector control. Scalar control is based on relationships valid in steady-state..

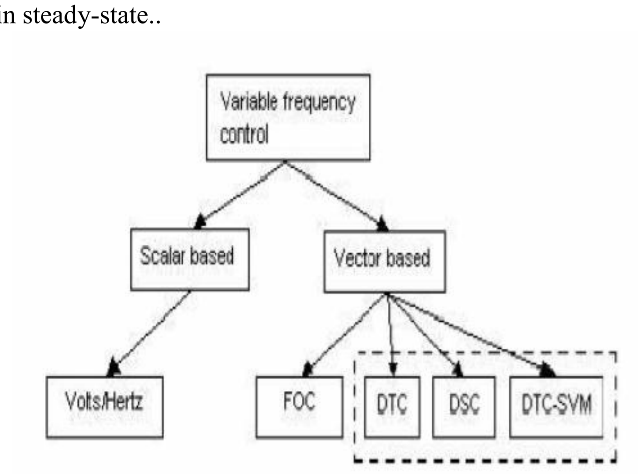


Figure 2.1, Some common control techniques used for PMSM. Control methods in the dashed box belong to the DTC family

Amplitude and frequency of the controlled variables are considered. In vector control amplitude and position of a controlled space vector is considered. These relationships are valid even during transients which is essential for precisetorque and speed control

A. Scalar Control

Scalar control is based on relationships valid in steady state. Only magnitude and frequency of voltage, current, etc. are controlled. Scalar control is used e.g. where several motors are driven in parallel by the same inverter.

B. Volts/Hertz control

Volts/Hertz control is among the simplest control schemes for motor control. The control is an open-loop scheme and does not use any feedback loops. The idea is to keep stator flux constant at rated value so that the motor develops rated torque/ampere ratio over its entire speed range. The voltage equations for a permanent magnet motor were derived in chapter 1. In qdcoordinates these equations are

$$v_q = r_s i_q + \omega\lambda_d + \frac{d}{dt}\lambda_q$$

$$v_d = r_s i_d - \omega\lambda_q + \frac{d}{dt}\lambda_d$$

where *vq* and *vd* are stator voltage, *rs* stator resistance, *i* stator current, ω angular velocity and λ is the flux linkage.
In stationarity the derivative terms disappears, furthermore, if speed is high the emf voltage, $\omega\lambda$, is relatively high and the resistive voltage drop may be ignored. In this case, if stator flux is to be kept constant, the voltage applied should be directly proportional to the rotor angular frequency. At lower speeds an extra boost voltage is applied to compensate for the resistive drop. The principle is valid only for stationarity when the derivative terms vanish.

C. Vector Control

The problem with scalar control is that motor flux and torque in general are coupled. This inherent coupling affects the response and makes the system prone to instability if it is not considered. In vector control, not only the magnitude of the stator and rotor flux is considered but also their mutual angle.

III. TRANSFORMATION TO qdo-FRAME

A. Reference Frames

The required transformation in voltages, currents, or flux linkages is derived in a generalized way. The reference frames are chosen to be arbitrary and particular cases, such as stationary, rotor and synchronous reference frames are simple instances of the general case. R.H. Park, in the 1920s, proposed a new theory of electrical machine analysis to represent the machine in d – q model. He transformed the stator variables to a synchronously rotating reference frame fixed in the rotor, which is called Park's transformation. He showed that all the time varying inductances that occur due to an electric circuit in relative motion and electric circuits with varying magnetic reluctances could be eliminated. In 1930s, H.C Stanley showed that time varying Inductances in the voltage equations of an induction machine due to electric circuits in relative motion can be eliminated by transforming the rotor variables to a stationary reference frame fixed on the stator. Later, G. Kron proposed a transformation of both stator and rotor variables to a synchronously rotating reference that moves with the rotating magnetic field.

B. Axes Transformation

We know that per phase equivalent circuit of the induction motor is only valid in steady state condition. Nevertheless, it doesn't hold good while dealing with the transient response of the motor. In transient response condition the voltages and currents in three phases are not in balance condition. It is too much difficult to study the machine performance by analyzing the three phases. In order to reduce this complexity the transformation of axes from 3 – Φ to 2 – Φ is necessary. Another reason for transformation is to analyze any machine of n number of phases. Thus, an equivalent model is adopted universally, that is'd – q model'.

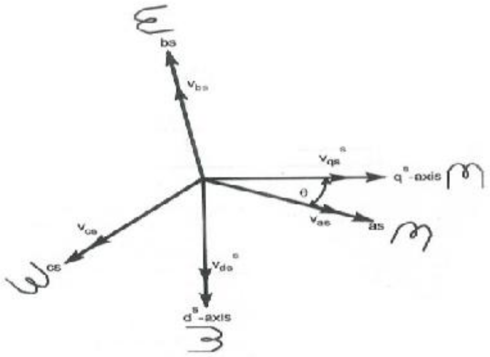


Fig 3.1(a). 3-ϕ to 2-ϕ Transformation

Consider a symmetrical three-phase induction machine with stationary as-bs-cs axis at 2π/3 angle apart. Our goal is to transform the three-phase stationary reference frame (as-bs-cs) variables into two-phase stationary reference frame (d^s-q^s) variables. Assume that d^s- q^s are oriented at θ angle as shown in fig: 3.1(a).

The voltages $v_{ds}{}^s \text{and} v_{qs}{}^s$ can be resolved into s-bs-cs components and can be represented in matrix from as,

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

The corresponding inverse relation is

$$\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} Cos\theta & Cos(\theta-120^0) & Cos(\theta+120^0) \\ Sin\theta & Sin(\theta+120^0) & Sin(\theta+120^0) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad 3.2$$

Here $v_{os}{}^s$ is zero-sequence component, convenient to set θ = 0 so that q^s axis is aligned with as-axis. Therefore ignoring zero-sequence component, it can be simplified as-

$$V_{qs}{}^s = \frac{2}{3} v_{as} - \frac{1}{3} v_{bs} - \frac{1}{3} v_{cs} = v_{as} \quad 3.3$$

$$V_{ds}{}^s = \frac{-1}{\sqrt{3}} v_{bs} + \frac{1}{\sqrt{3}} v_{cs} \quad 3.4$$

Equations 3.3 & 3.4 consistively called as *Clark Transformation.*

Figure 3.1 (b) shows the synchronously rotating d^e-q^e axes, which rotate at synchronous speed w_e with respect to the d^s-q^s axes and the angle $\theta_y = \omega_e \square t$. The two-phase d^s-q^s windings are transformed into the hypothetical windings mounted on the d^e-q^e axes. The voltages on the d^s-q^s axes can be transformed (or resolved) into the d^e-q^e frame as follows:

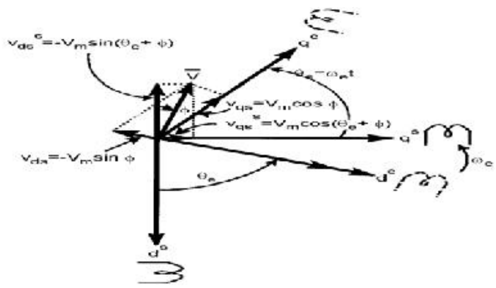


Fig 3.1(b) stationary frame d^s-q^s to dynchronously rotating frame d^e-q^e transformation

$$v_{qs} = v_{qs}^s \cos\theta_e - v_{ds}^s \sin\theta_e \ldots\ldots 3.5$$

$$v_{ds} = v_{qs}^s \sin\theta_e + v_{ds}^s \cos\theta_e \ldots\ldots 3.6$$

Constitutively eq 2.5 and 2.6 are known as *Park Transformation.*

For convenience, the superscript 'e' has been dropped from now on from the synchronously rotating frame parameters. Again, resolving the rotaing frame parameters into a stationary frame, the relations are

$$v_{qs}^s = v_{qs} \cos\theta_e + v_{ds} \sin\theta_e \ldots\ldots 3.7$$

$$v_{ds}^s = -v_{qs} \sin\theta_e + v_{ds} \cos\theta_e \ldots\ldots 3.8$$

CONSTITUTIVELY EQ 3.7 AND 3.8 ARE KNOWN AS *INVERSE PARK TRANSFORMATION*

IV.CONTROL STRATEGY FOR DTC

The block diagram of direct torque and flux control is shown in Figure 6 explains the control strategy. The speed control loop and the flux program as a function of speed are shown as usual and will not be discussed. The command stator flux Ψ_s^* and torque T_e^* magnitudes are compared with the respective estimated values and the errors are processed through hysteresis-band controllers, as shown. The flux loop controller has two levels of digital output according to the following relations

$$H_\psi = 1 \quad \text{for} \quad E_\psi > +HB_\psi \tag{4.1}$$

$$H_\psi = -1 \quad \text{for} \quad E_\psi < -HB_\psi \tag{4.2}$$

$$H_{Te} = 1 \quad \text{for} \quad E_{Te} > +HB_{Te} \tag{4.3}$$

$$H_{Te} = 0 \quad \text{for} \quad -HB_{Te} < E_{Te} < +HB_{Te} \tag{4.5}$$

The feedback flux and torque are calculated from the machine terminal voltages and currents. The signal computation block also calculates the sector number S(k) in which the flux vector Ψ_s lies.

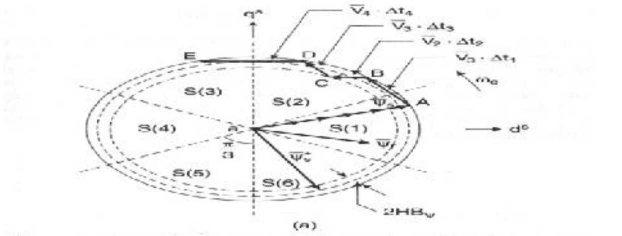


Fig.4.1 Flux Sector

The voltage vector receives the input signals H_Ψ H_{Te} and S(k) generates the appropriate control voltage vector (switching states) for the inverter by lookup table, which is shown in Table-1 (the vector sign is deleted). The inverter voltage vector (six active and two zero states) and a typical Ψ_s are shown in Figure 5. Neglecting the stator resistance of the machine.

$$\overline{V_s} = \frac{d}{dt}(\overline{\psi_s}) \tag{4.6}$$

(or)

$$\Delta\overline{\psi_s} = \overline{V_s}\,.\Delta t \tag{4.7}$$

The flux in machine is initially established to at zero frequency (dc) along the trajectory OA shown in Figure 5. With the rated flux, the command torque is applied and the Ψ_s^* vector starts rotating.

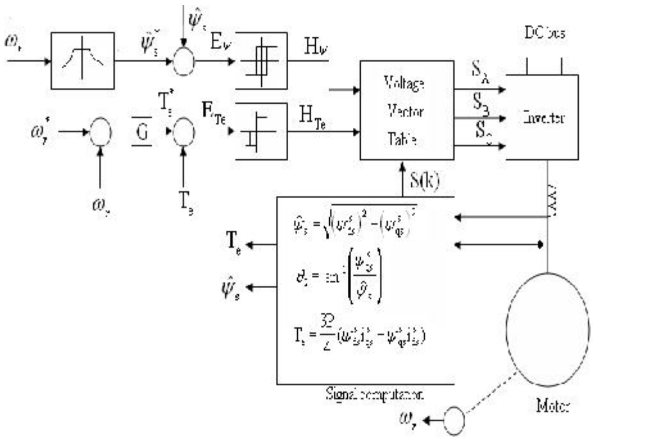


Fig.4.2 Direct Torque and Flux Control Block Diagram

TABLE I
SWITCHING TABLE OF INVERTER VOLTAGE VECTORS

H_ψ	H_{Te}	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
I(1)	I(1)	V2	V3	V4	V5	V6	V1
	I=(0)	V0	V7	V0	V7	V0	V7
	ID(-1)	V6	V1	V2	V3	V4	V5
D(-1)	I(1)	V3	V4	V5	V6	V1	V2
	I=(0)	V7	V0	V7	V0	V7	V0
	ID(-1)	V5	V6	V1	V2	V3	V4

TABLE 2
FLUX AND TORQUE VARIATIONS DUE TO APPLIED VOLTAGE VECTOR

Voltage vector	V1	V2	V3	V4	V5	V6	V0 or v7
Ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

V. MODEL REFERNCE ADAPTIVE SYSTEM (MRAS)

Figure 15 shows the simulink block diagram Model Referencing Adaptive System (MRAS). Which is consists Two blocks one is called Reference Model and other is Adaptive Model. The voltage model's stator-side equations, are defined as a Reference Model and the simulink block diagram of Reference Model is shown in Fig 11. The Adaptive Model receives the machine stator voltage and current signals and calculates the rotor flux vector signals, as indicated by equations, which is shown in Fig 12. By using suitable adaptive mechanism the speed ω_r, can be estimated and taken as feedback.

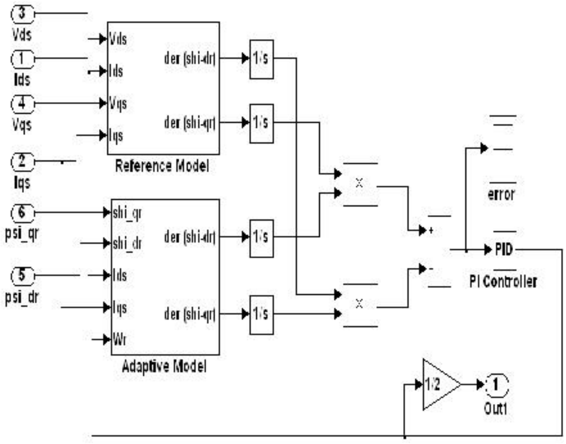


Fig 12: Simulink block diagram for Model Referencing Adaptive System with pi

VI. MATLAB BASED MODELING AND PERFORMANCE

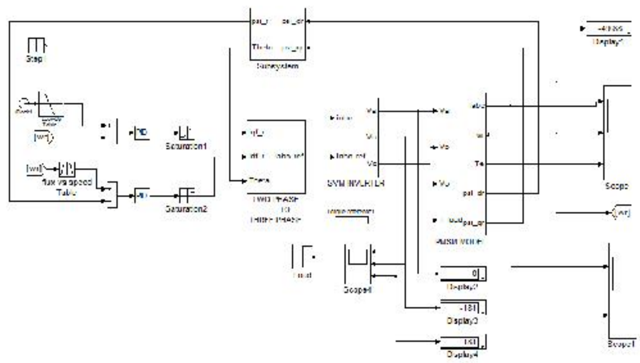


Fig 6.1 Block diagram of SVM-DTC

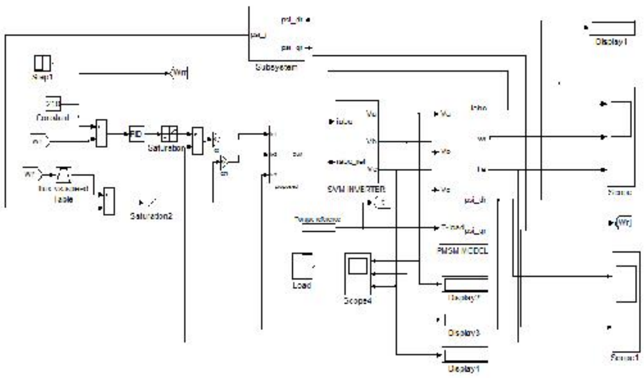


Fig 6.2 Block diagram of the proposed DTC

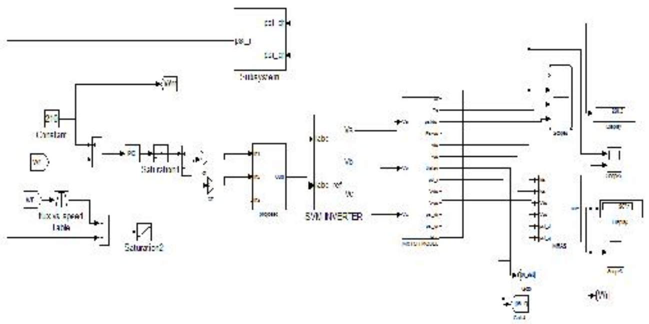
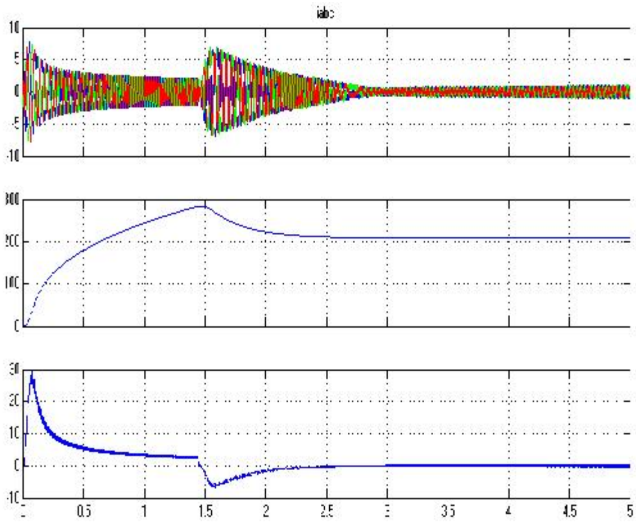


Fig 6.3 Block diagram of the proposed DTC.with MRAS



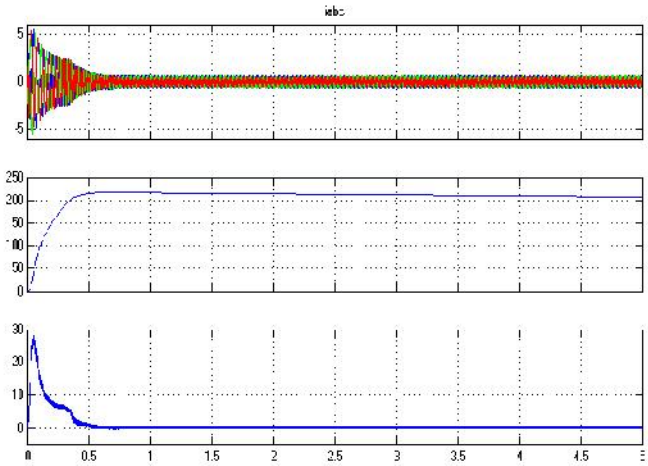
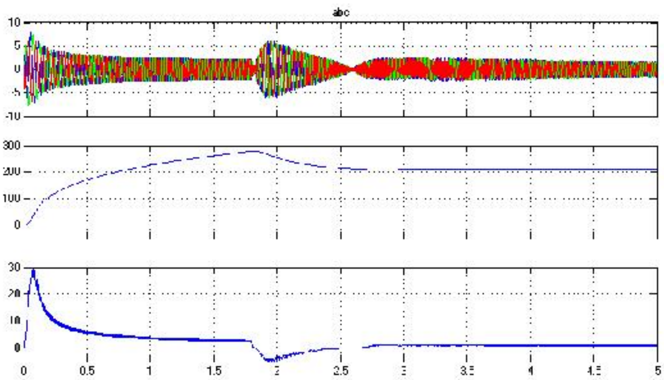


Fig 6.4 Steady response at 100% rated speed for classical DTC, DTC1



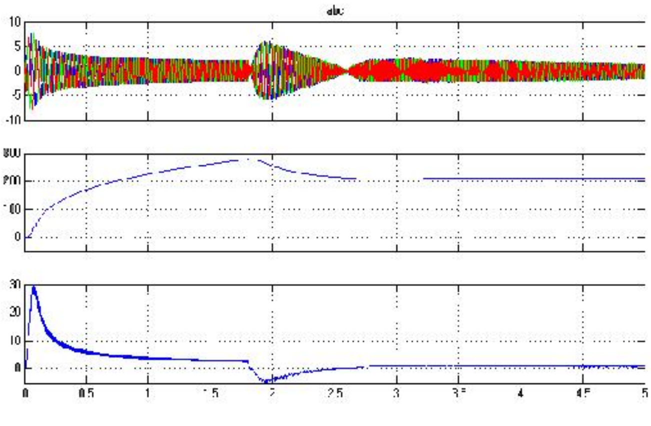


Fig 6.5 Steady-state response at 10% rated speed for classical DTC, DTC1

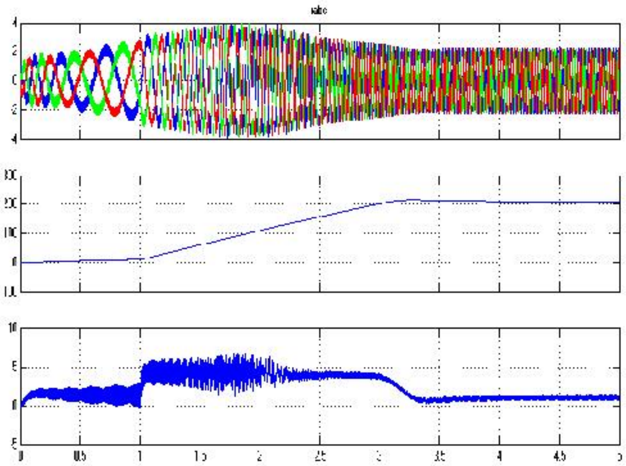


Fig 6.6 Start-up responses from standstill to rated speed for DTC1

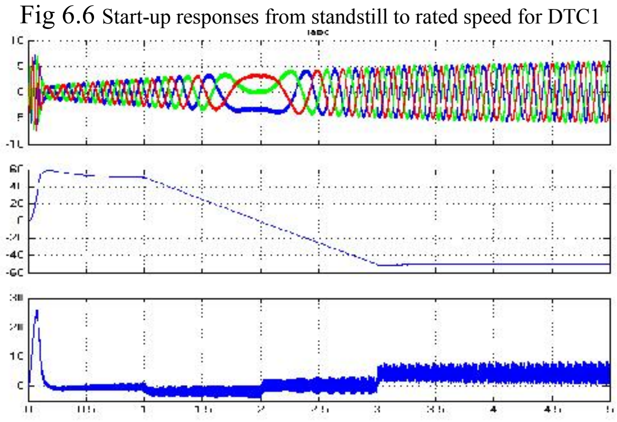


Fig 6.7 Speed reversal from 500 to −500 r/min

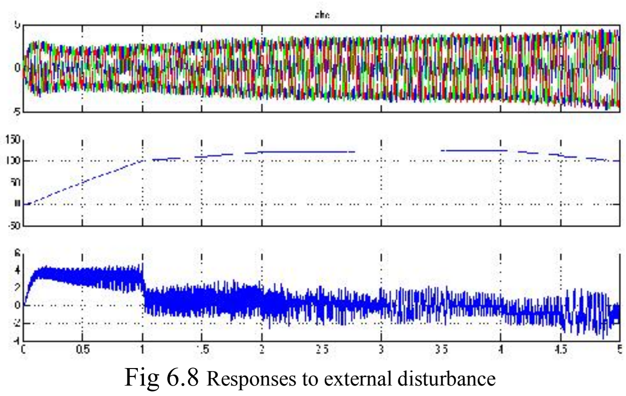


Fig 6.8 Responses to external disturbance

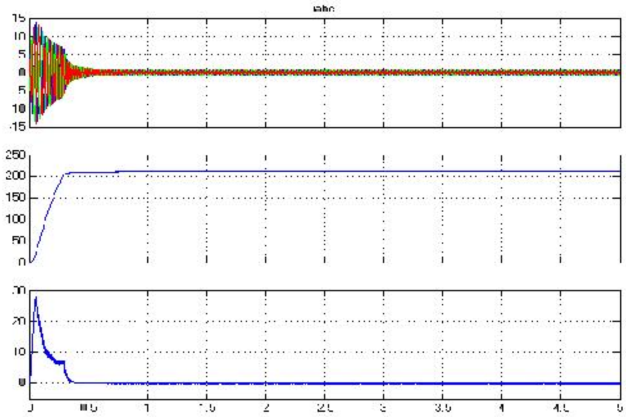


Fig 6.9 Proposed model with MRAS

VII. CONCLUSIONS

The paper presents a discrete space vector pulse-width modulation applied to DTC of PMSM and Sensorless control.The benefits of Vector control without using any shaft encoder which is a compromise between performance and low complexity because the use of look-up tables. The mathematical model of the drive system has been developed and results have been simulated. Simulation results of Vector Control and Sensorless Control of DTC- PMSM using MRAS technique using Pi controller were carried out by using Matlab/Simulink and from the analysis of the simulation results, the transient and steady state performance of the drive have been presented and analyzed.

From the simulation results, it can be observed that, in steady state there are ripples in torque wave and also the starting current is high.

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IX. AUTHORS

Jyothi Mangaveni Ch is currently doing her Post Graduate course in Power and Industrial Drives in Electrical and Electronics Engineering Department, Dadi Institute of Engineering and Technology, Anakapalle, Visakhapatnam, India, Bachelor degree in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University- Kakinada, Andhra Pradesh, India, in 2010.
Mail id: Jyothi.chitta@gmail.com

Srinivasa Rao M received his Master degree from Jawaharlal Nehru Technological University-Kakinada, India, and Bachelor degree from Jawaharlal Technological University- Hyderabad, India. He worked as an Assistant Engineer(E) for Damodar Valley Corporation. He is Currently working as an Associate Professor of Electrical and Electronics Engineering Department at Dadi Institute of Engineering and Technology, Anakapalle, Visakhapatnam, India. He presented several Technical papers in various National and International Journals in this area. And He is providing technical assistance to sevaral solar modules manufacturing organizations.