COMPARATIVE ANALYSIS OF THE VECTOR CONTROL AND THE DIRECT TORQUE CONTROL PMSM DRIVES

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ABSTRACT

Permanent Magnet Synchronous Motors (PMSM) encompass escalating awareness in topical years for industrial drive applications. The elevated efficiency, high steady state torque density and simple controller of the Permanent Magnet (PM) motor drives compared to the induction motor drives make them a good substitute in scores of application. The paper presents the two imperative control strategies for 3-phase AC motors i.e. Vector Control and Direct Torque Control (DTC) applied to PMSM with their respective comparative study. The recital of the developed model of PMSM drive is found to operate adequately with the controllers in fleeting as well as steady state. The response of vector control for PMSM drive is observed to be good load perturbation and transient condition, whereas DTC is better in terms of power converter utilization at higher speeds and rated loads.

Keywords: *Permanent Magnet Synchronous Motors (PMSM), Vector Control, Direct Torque Control, PI Controller*

I. INTRODUCTION

A Permanent Magnet Synchronous Motor (PMSM) uses permanent magnets such as Samarium Cobalt (First generation rare earth magnet-SmCo), Neodymium Iron-Boron (Second generation rare earth magnet-NdFeB), etc. to generate the air gap magnetic field rather than using electromagnets. Development of magnet technology has endorsed augmented power/torque density and efficiency of the PM machines. Adding up, slip rings are eliminated thereby recuperating the reliability and plummeting the maintenance of PM machines as compared to conventional machines. Thus, with regard to the requisite of maintaining a low level of electromagnetic torque ripple, better efficiency, higher reliability and enhanced control properties, Permanent Magnet Synchronous Motors (PMSM) powered by a sinusoidal current wave is preferred in modern drives. Bimal K. Bose [1] showed that an Interior Permanent Magnet (IPM) synchronous motor possess special features for adaptable speed operation which distinguished them from other classes of ac machines. They were robust high power density machines capable of operating at high motor and inverter efficiencies over wide speed ranges, together with considerable range of constant power operation. Takahashi and Noguchi [2] projected the original concept of DTC for appliance in Induction Motors. Their initiative was to control the stator flux linkage and the torque directly and not via controlling the stator current. Kuan-Teck Chang et. al. [3] introduced an optimal control system synthesis method which can achieve vector and speed control simultaneously for Permanent-Magnet Synchronous Motor (PMSM) drives. A pseudo-linearized PMSM model is dynamically constructed through the state detection, and subsequently an optimal speed controller is developed based on this linearized model. Bhim

Singh et. al. [4] analyzed the performance of the Field Oriented Control (FOC) of Permanent Magnet Synchronous Motor (PMSM) drive with a PID (Proportional Integral Derivative) in dc link voltage control and Fuzzy PID for speed control in closed loop operation thus inferring that the fuzzy controller provides a better response to the drive system especially in the steady state condition. Alexander Verl and Marc Bodson [5] discussed the problem of maximizing the torque of permanent magnet synchronous motors in the presence of voltage and current constraints. They have given the formulae suitable for the operation with voltage and current source inverters and for real-time computation. Zhong L.Rahman et. al. [6] presented a direct torque control scheme for permanent magnet synchronous motor drives, where current controllers followed by PWM or hysteresis comparator are not used. The characteristics of a permanent-magnet synchronous motor are influenced greatly by the back-electromotive force waveforms in the motor, which are directly related its magnet shape. Therefore attempts are made by researchers to optimize the radius of the magnet with respect to number of poles, rotor size, and magnet thickness for the best results regarding the total harmonic distortion. Further several designs are tried and being developed for the control of PMSM in the field weakening (constant power) region without any danger of permanent loss of magnetisation employing techniques like Finite Element Modelling (FEM). The paper basically analyses the performance of PMSM under direct torque control and vector control strategy along with their respective comparative study through simulink models.

II. PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM) MODEL

A Permanent Magnet Synchronous Motor (PMSM) has significant advantages, attracting the attention of researchers and industry for use in many applications. These motors supplant the conventional motors used hitherto, in particular the standard DC motors with mechanical commutators & induction motors. With regard to the prerequisite of maintaining a low level of electromagnetic torque ripple and much better control properties, the Permanent Magnet Synchronous Motors, powered by a sinusoidal current wave, are usually used in most of the modern drives [2]. The operation of a brushless PM motor relies on the conversion of electrical energy to magnetic energy and then from magnetic energy to mechanical energy. It is possible to generate a magnetic rotating field by applying sinusoidal voltages to the 3 stator phases of a 3 phase motor. A resultant sinusoidal current flows in the coils thus generating the rotating stator flux. The rotation of the rotor shaft is then created by attraction of the permanent rotor flux with the stator flux.

III. CONTROL STRATEGY OPTIONS

The control of PMSM drive is divided into Scalar Control and Vector Control. Scalar Control is based on relationships between the magnitude and the frequency of voltage/current applied. The control is used where a motor is not requisite to experience quick speed changes and load perturbation. The control is generally an open-loop scheme and does not use any feedback loops. The problem with scalar control is that motor flux and torque in general are inherently coupled which affects the response and makes the system prone to instability. On the contrary, in Vector control, not only the magnitude of the stator and rotor flux, but also their mutual angle, is considered. Vector Control or Field Oriented Control (FOC) has demonstrated that an induction motor or synchronous motor could be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to attain a desired objective. The control strategy for vector control of PMSM is shown in Fig.1. The PM synchronous motor is fed by a +voltage source inverter. The speed control loop uses a PI regulator to produce the flux and torque references for the vector controller which computes the three reference motor line currents corresponding to the flux and torque references and then feeds the motor with these currents using a three-phase current regulator.

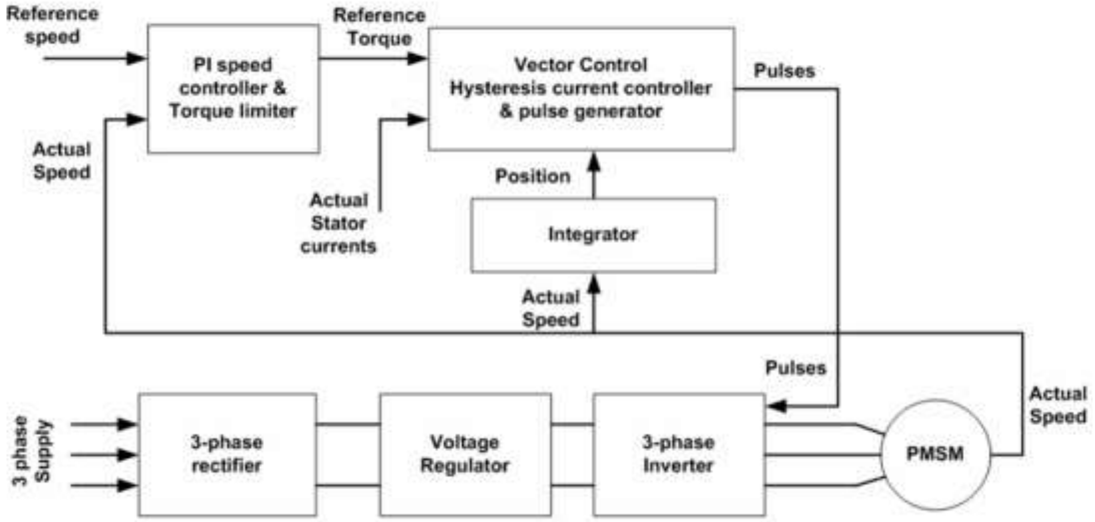

Fig.1Schematic Diagram for Control of PMSM Using FOC

IV. SIMULATION OF FIELD ORIENTED CONTROL (FOC) OF PMSM DRIVE

The entire system is divided in various subsystems like DC bus voltage regulator, speed controller and vector controller. Also blocks like 3-phase supply, 3-phase diode rectifier, 3-phase inverter and PMSM machine model are designed for the realisation of the drive control. The basic Simulink model of control of PMSM using vector control is shown as in Fig.2.

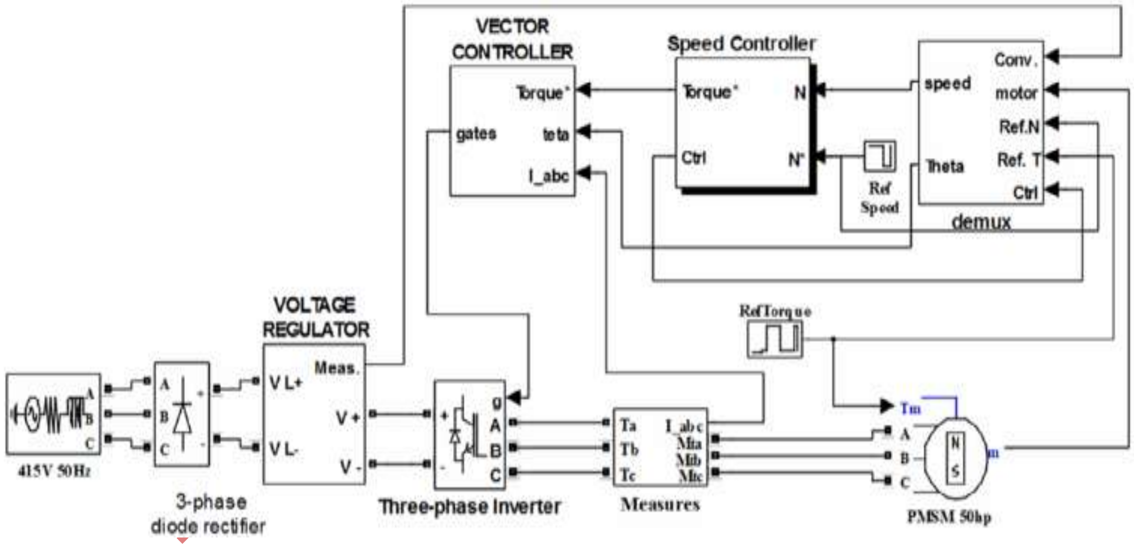

Fig.2 Simulink Model of Control of PMSM Using Vector Control

The voltage regulator keeps the rectified output voltage of 3- phase diode rectifier within specified limits as per the input requirement of the inverter, mainly during starting period. This regulator also provides braking resister to squander the stored energy within the motor drive during braking/deceleration operation. The PI controller is used as the speed controller to improve the steady-state performance by increasing the type of the system and at the same time, improving the relative stability. The transfer function of the PI controller is given as:

$$D(z) = Kp + Ki\frac{Ts(z+1)}{2(z-1)}$$

Speed controller compares the actual speed obtained from speed sensor of motor & the reference speed to generate reference torque which when passed through speed ramp block limits the rising & falling rate of the speed signal. Vector controller mainly gives pulses to the inverter. Since vector control to be performed is below the base speed, the d-axis reference current (id*) is kept zero, whereas the q-axis reference current (iq*) is obtained from reference torque value. These two currents are then converted to stator frame of reference (iabc*) to compare it with actual stator currents (iabc).

V. SIMULATION OF DIRECT TORQUE CONTROLLED (DTC) PMSM DRIVE

The DTC subsystem consists of torque and flux calculator, flux and torque hysteresis, flux sector seeker and switching table as shown in Fig.3 of the simulink model of Direct Torque Controlled PMSM drive. The output of the switching table is applied to switching control subsystem, whose function is to appropriate pulses to the inverter.

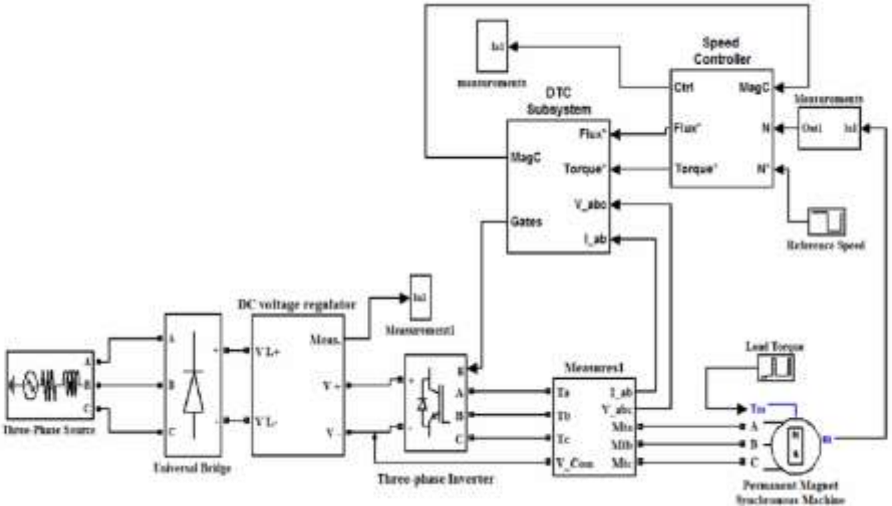

Fig.3 Simulink Model of Direct Torque Controlled PMSM Drive

Flux and torque calculator is used to determine the actual value of the torque and flux linkages. The stator flux linkage is estimated by taking the integral of difference between the input voltage and the voltage drop across the stator resistance as: [10],

$\lambda ds = \int(Vds – R\ ids)\ dt$

$\lambda qs = \int(Vqs – R\ iqs)\ dt$

During the process, the location of stator flux linkage (θ) is determined by the load angle (δ) i.e the angle between the stator and rotor flux linkage. The load angle must be known so that the DTC chooses an appropriate set of vectors depending on the flux location. The load angle is determined by

$$\delta = \tan^{-1}\frac{\lambda_{ds}}{\lambda_{qs}}$$

The electromagnetic torque is estimated as:

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

If the actual torque is smaller than the reference value, the comparator outputs at state 1 or otherwise. The Flux & Torque Hysteresis course contains a two-level hysteresis comparator for flux control and a three-level hysteresis comparator for the torque control. In Torque Hysteresis**,** the bandwidth value is the total bandwidth distributed symmetrically around the torque set point in N-m and in case of Flux Hysteresis, the stator flux hysteresis bandwidth value is the total bandwidth distributed symmetrically around the flux set point in Weber.

The hysteresis comparator states, φ and τ, together with the section number θ, are used by the switching table to choose an appropriate voltage vector. A high hysteresis state increases the corresponding quantity and vice versa. The selected voltage vector is sent to the Voltage Source Inverter and then synthesized.

VI. RESULTS

The simulation of the two popular control strategies, vector control and direct torque control checks the performance which states the effectiveness of the control strategy. The speed response, the stator current waveforms, the DC bus voltages and currents and torque ripples are considered as the main performance parameters in the paper.

6.1 Performance Analysis of Vector Controlled PMSM Drive

The system built in MATLAB simulink for a Vector Controlled PMSM drive system is tested for starting, load perturbations and speed reversals. Fig.4 shows the simulation result of the actual and reference speed, the stator current Ia, actual and reference torque, stator currents in rotor frame of reference I_{dq} and the DC link voltage.

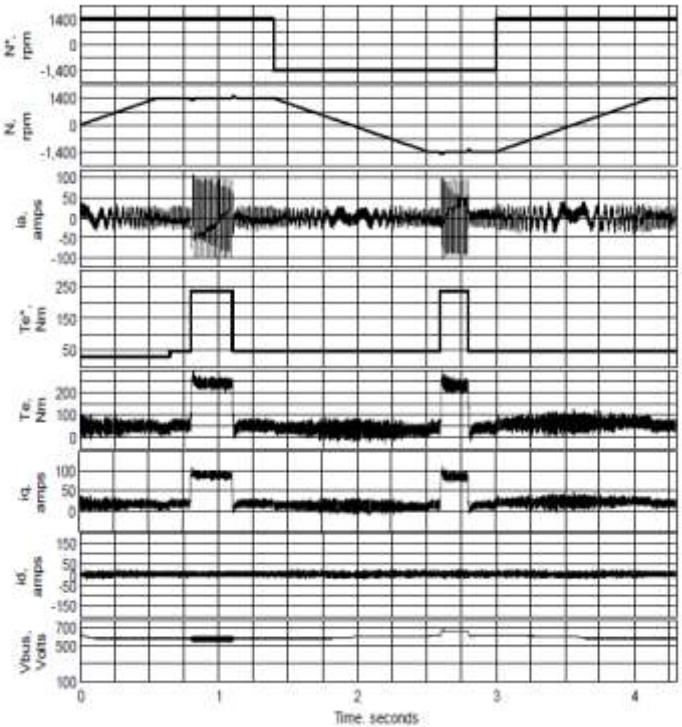

Fig.4 Simulation Results Of Vector Control Of PMSM (I) Reference Speed (Ii) Actual Speed (Iii) Stator Currents Iabc (Iv) Reference Torque (V) Actual Torque(Vi) Q-Axis Stator Current Iq (Vii) D-Axis Stator Current Id (Viii) DC Bus Voltage

The actual speed follows reference speed as per the speed controller settings and the motor parameters. The rate of rise or fall of speed is altered but the final response of the drive depends on torque saturation settings of speed controller (PI controller) of the motor. The torque saturation settings decide the currents flowing through the devices. As the step of the speed is more, the settling time increases. In other words, actual speed reaches at the desired level with delay. A short duration dip in the speed occurs at the time of increase in the load or a sharp rise in the speed is observed during decrease in the load but their duration is too small. Fig.4 shows that due to increase in the load torque, the phase currents magnitude increases. While settling down, current spikes are observed. Also there is a decrease in the frequency during acceleration period. The voltage regulator regulates the bus voltage within the specified range. However sudden speed reversal and increase in load torque increases the DC bus voltage.

6.2 Performance Analysis of Direct Torque Controlled PMSM Drive

The simulation is carried out for the transient conditions of speed and load which are kept same as those in vector control simulation of the PMSM. Fig.5 shows the simulation results of DTC of PMSM giving stator current Ia , reference speed, actual speed, reference torque, actual torque, q-axis stator current ‘iq’ and d-axis stator current ‘id’.

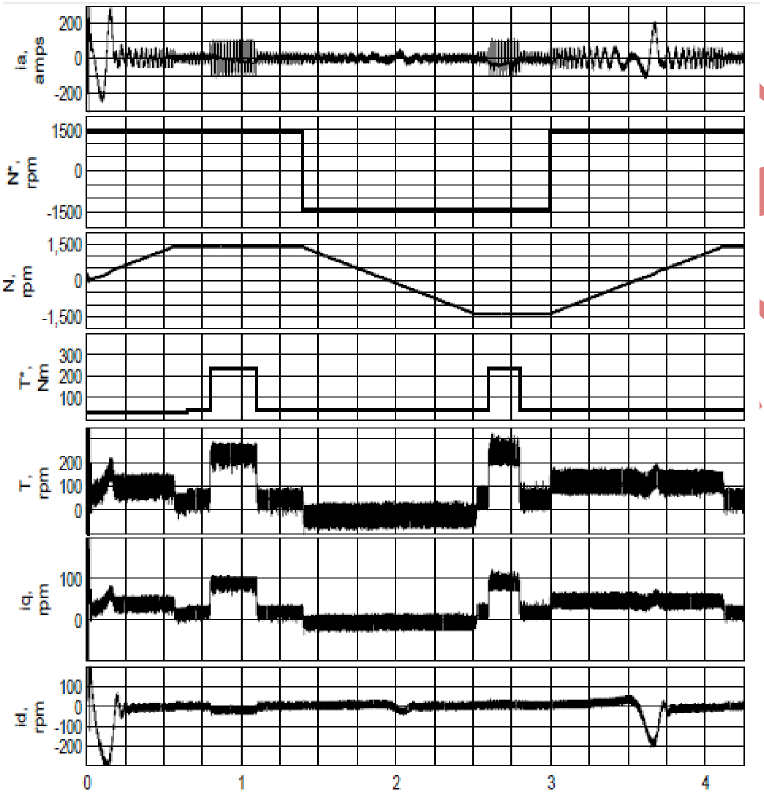

Fig.5 Simulation Results Of DTC Of PMSM (I) Stator Current Ia (Ii)Reference Speed(Iii) Actual Speed (Iv) Reference Torque (V) Actual Torque (Vi) Q-Axis Stator Current Iq (Vii) D-Axis Stator Current Id

Fig.5 shows the initial increase in the magnitude because of both acceleration and load torque which settles down quickly. During load increase, there is an increase in the stator currents. Because of the change in flux linkages, change in d-axis current is observed particularly at the time of speed reversal. The torque component of stator current ‘iq’ responds to the change in load torque. At higher speeds, it is observed that the DTC has a good dynamic performance. The response of DTC under high speed has no overshoot and quick start-up viewing that the response time is less.

6.3 Comparative Study of Vector and Direct Torque Controlled PMSM Drive

The study is carried out on the currents drawn at different speeds and at different loading under steady state conditions. The rms values of stator current of phase ‘a’ and average values of d-axis and q- axis components of the stator currents in rotor frame of reference during vector control and direct torque control of the PMSM drive are tabulated in Table 1. Since the reference speed of the motor is below the base speed, the d-axis component of stator current ‘I_d’ is negligible during vector control. But q-axis component of the stator current ‘I_q’ increases as the load on the motor is increased resulting in the increase in the amplitude of ‘I_a’, the phase ‘a’ stator current. Similar observations for 'I_q' and 'I_a' takes place during the application of direct torque control on the drive. But the magnitude of 'I_d' is comparable to that of 'I_q' because of the change in amplitude and position of the flux vector as per the torque and speed demand.

Table1. Stator Current during Vector Control and DTC

Reference Speed %	Load Torque %	Ia (rms) Amps		Id (Average) Amps		Iq (Average) Amps	
		Vector Control	Direct Torque Control	Vector Control	Direct Torque Control	Vector Control	Direct Torque Control
25	20	17.31	17.38	00.45	14.05	18.34	19.71
	40	29.96	29.37	00.32	24.74	35.51	36.36
	60	39.59	39.23	00.35	38.14	53.08	53.53
	80	47.28	45.48	00.05	53.33	70.56	71.00
	100	51.71	51.50	01.14	70.46	88.04	88.39
50	20	14.77	16.31	01.64	10.54	18.22	20.07
	40	26.83	28.28	01.80	15.14	36.26	36.66
	60	38.29	41.33	00.98	21.27	53.65	53.82
	80	49.27	54.80	02.19	28.79	70.28	71.26
	100	62.80	67.63	01.72	37.35	88.51	88.52
75	20	13.98	17.18	03.10	09.88	18.27	20.50
	40	25.02	30.13	02.38	12.61	36.35	37.03
	60	38.03	43.81	02.21	16.37	53.46	54.33
	80	52.36	57.33	02.16	21.73	71.27	71.60
	100	66.81	70.86	02.66	27.91	88.60	88.92
100	20	14.19	15.70	01.66	09.34	19.07	20.44
	40	26.31	27.26	01.81	10.96	36.57	36.79
	60	38.38	39.24	01.79	14.92	54.14	54.60
	80	50.50	52.21	02.26	18.63	71.70	71.87
	100	63.21	65.13	01.75	23.58	89.21	88.96

The variation in the current magnitude verses load is observed to be almost uniform at higher speeds. Fig.6-7 shows that the magnitude of 'I_d' is almost constant at base speed and that of 'I_q' varies only with the load and its variation with speed is almost negligible. Anon, the variation of 'I_q' with load is almost uniform showing that during vector control, the torque and speed are completely decoupled. Fig.8 shows the stator phase current variations during DTC for different load and speed variations. The steady state magnitudes of the stator currents are almost same as those in case of vector controlled PMSM drive as shown in Figure 3.24. From Figure 3.28 it is clear that the motor draws more amount of current at speed nearer to 75% of the base speed than other speeds.

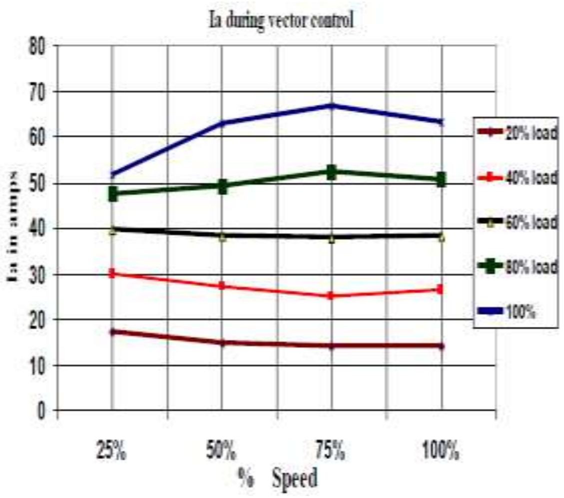

Figure 3.23: Stator Phase Current Variations during Vector Control

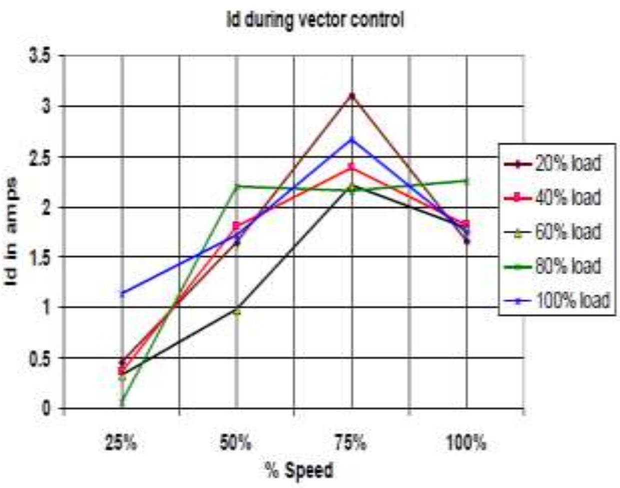

Figure 3.24: D-Axis Current Variations during Vector Control

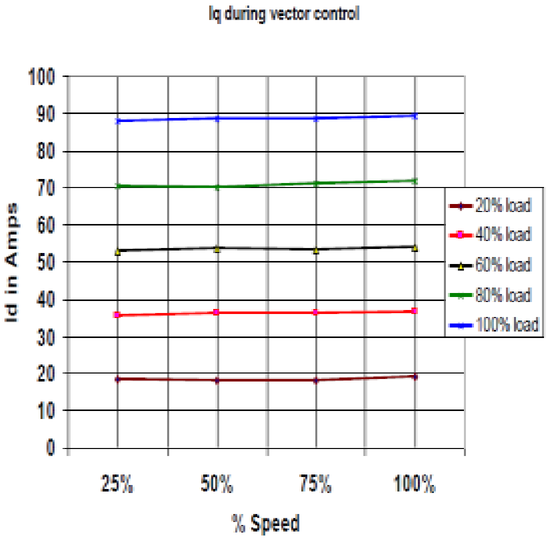

Figure 3.25: Q-Axis Current Variations during Vector Control

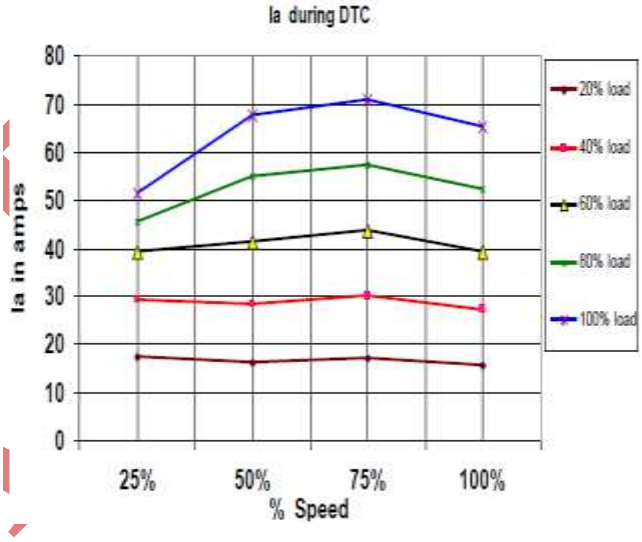

Figure 3.26: Stator Phase Current Variations During DTC

VII. CONCLUSION

The two important control strategies for 3-phase AC motors, vector control and DTC have been applied to PMSM and simulation results are obtained. The performance of developed model of PMSM drive is found to work satisfactorily with the developed controllers in transient as well as steady state. The result shows that the wide range of speed can be can be covered in vector control. The response of vector control for PMSM drive is observed to be good load perturbation and transient condition, whereas DTC is better in terms of power converter utilization at higher speeds and rated loads.

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