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Simulation and Dynamic Response of Closed Loop Speed Control of PMSM Drive Using Fuzzy Controller

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Abstract:

This paper presents a closed loop speed control of PMSM drive.The PMSM lacks a commutator and is therefore more reliable than the DC motor. The PM synchronous motor also has advantages when compared to an AC induction motor. Because a PMSM achieves higher efficiency by generating the rotor magnetic flux with rotor magnets, a PMSM is used in high-end white goods (such as refrigerators, washing machines, dishwashers) high-end pumps; fans; and in other appliances which require high reliability and efficiency.

This application creates a speed closed-loop PM synchronous drive using a vector control technique. It also illustrates the use of the PE's dedicated motor control libraries.The vector control scheme of a PMSM drive has been implemented using the developed simulation model. In the developed model, speed and torque as well as the currents of voltage source inverters components can be effectively monitored and analyzed. Also, total harmonic distortion (THD) of the PMSM drive also analysed.

The developed simulation model has been implemented using Matlab and the dynamic response of PMSM drive has been analyzed for constant speed, varying torque and variable speed constant torque operation. The proposed concept can be applied to fuzzy logic control system in order to improve the dynamic response, stability and efficiency and to reduce the THD of the system by using MATLAB/SIMULATION software and the results are verified.

I.Introduction:

In recent years, many DC drives were replaced by brushless drives. PMSM gained much attention and has become the most used drive in machine tool servos and modern speed control applications. The inherent advantages of the machine include high efficiency, high power factor, high power density, easy maintenance, fast dynamic response. PMSM replaces Induction motor (IM) and Synchronous motor (SM) in several applications due to its higher efficiency, high power density and high torque to inertia ratio [1]. Rotor of PMSM is made up of permanent magnet so there is no need of supplying magnetizing current through stator to produce air gap flux.

SM requires dc excitation on the rotor, which is supplied by brushes and slip rings; it leads to rotor losses and requires regular maintenance [2]. In PMSM rapid torque build up required by, variable speed and fast dynamic response drives, could be achieved by stator current control technique. PMSM is a topic of interest for last twenty years. Vector control technique is one of the most common closed loop control technique used in a PMSM drive. Vector control eliminates oscillating flux, torque responses in inverter fed induction motor and synchronous motor drives.

This method has further classification, which includes constant torque angle control, Unity power factor control, and constant mutual air gap flux-linkages control, optimum-torque-per-ampere control and flux-weakening control. The choice of these methods depends on mainly on the type of application and the load characteristics.

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Hence, it is always essential to perform a simulation study prior to designing a PMSM drive for choosing the appropriate control algorithm for a particular application. The mathematical model of PMSM as such has been well established in literature [2] and [3]. Incorporation of PMSM model along with the inverter model and load characteristics is essential to represent a complete drive system. Such a simulation model has been reported for a BLDC drive [4]. Also the modeling of complete PMSM drive is reported in [2].

This paper proposes a system simulation model for a complete PMSM drive based on the mathematical model of an inverter fed PMSM implemented using MATLAB\Simulink, which could be used for simulating various control algorithms.In the developed model, speed and torque as well as the currents of voltage source inverters components can be effectively monitored and analyzed.

II. Mathematicalmodel of PMSM:

The mathematical model of PMSM available in the existing literature [1] and [5] has been presented in this section to provide a basis for the subsequent sections. The stator of the PMSM and the wound rotor synchronous motor are similar. The permanent magnets used in the PMSM are of a modern rare-earth variety with high resistivity, so induced currents in rotor are negligible. In addition, there is no difference between the back EMF produced by a permanent magnet and that produced by an excited coil. Hence the mathematical model of a PMSM is similar to that of the wound rotor SM. The rotor reference frame is chosen because the position of the rotor magnets determines the instantaneous induced emfs and subsequently the stator currents and torque of the machine independently of the stator voltages and currents. The following assumptions are considered in the derivation.

- Saturation and parameter changes are neglected
- Stator windings are balanced with the induced EMF is sinusoidal
- Eddy current and hysteresis losses are negligible
- There are no field current dynamic
- There is no cage on the rotor

The equivalent circuits of PMSM in d, q axes in rotor reference frame are shown in fig 1 and fig 2 respectively

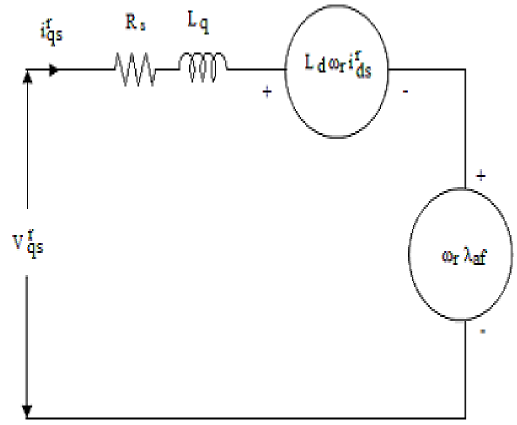

Fig. 1.Stator q-axis equivalent circuit

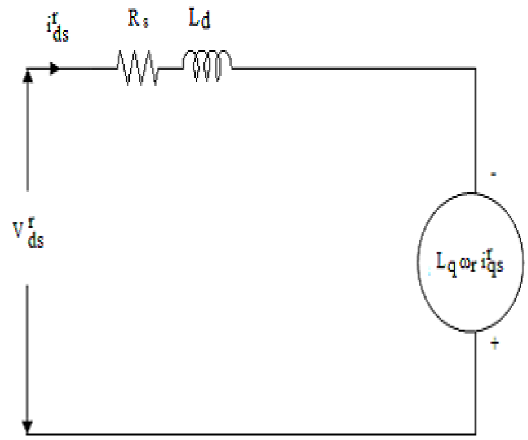

Fig. 2.Stator d-axis equivalent circuit

With these assumptions, the stator voltage d-q equations of the PMSM in the rotor reference frame is given by equations (1) and (2)

$$V^r_{qs} = R_s i^r_{qs} + p\lambda^r_{qs} + \omega\lambda^r_{ds} \quad (1)$$

$$V^r_{ds} = R_s i^r_{ds} + p\lambda^r_{ds} - \omega\lambda^r_{qs} \quad (2)$$

The stator flux linkages is given by equations (3) to (5)

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$$\lambda_{qs}^{r} = L_q i_{qs}^{r} \quad (3)$$

$$\lambda_{ds}^{r} = L_d i_{ds}^{r} + L_m i_{fr} \quad (4)$$

$$L_m i_{fr} = \lambda_{af} \quad (5)$$

Vrqs and Vds r are the d, q axes voltages, iqs r and ids r are the d, q axes stator currents in rotor reference frame, Ld and Lq are the d, q axis inductances and λd and λq are the d, q axis stator flux linkages in rotor reference frame, while Rs and ωr are the stator resistance and inverter frequency respectively. λaf is the flux linkage due to the rotor magnets linking the stator. Equations (6) and (7) is obtained by substituting equations (3) to (5) in (1) and (2)

$$V_{qs}^{r} = R_s i_{qs}^{r} + p(L_q i_{qs}^{r}) + \omega_r (L_d i_{ds}^{r} + \lambda_{af}) \quad (6)$$

$$V_{ds}^{r} = R_s i_{ds}^{r} + p(L_d i_{ds}^{r}) - \omega_r (L_q i_{qs}^{r}) \quad (7)$$

Equations (8) and (9) is obtained by rearranging equations (6) and (7) in matrix form

$$\begin{bmatrix} V_{qs}^{r} \\ V_{ds}^{r} \end{bmatrix} = \begin{bmatrix} R_s + pL_q & \omega_r L_d \\ -\omega_r L_q & R_s + pL_d \end{bmatrix} \begin{bmatrix} i_{qs}^{r} \\ i_{ds}^{r} \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_{af} \\ 0 \end{bmatrix} \quad (8)$$

The electromagnetic torque developed by the motor is given by equation (9)

$$T = \frac{3}{2}\frac{P}{2}\{\lambda_{ds}^{r} i_{qs}^{r} - \lambda_{qs}^{r} i_{ds}^{r}\} \quad (9)$$

The three phase stator voltage equations is given by equations (10) to (12)

$$V_{as} = V_m \sin \omega t \quad (10)$$

$$V_{bs} = V_m \sin (\omega t - \frac{2\pi}{3}) \quad (11)$$

$$V_{cs} = V_m \sin (\omega t - \frac{2\pi}{3}) \quad (12)$$

Vas ,Vbs and Vcs are a-phase, b-phase and c-phase stator voltages respectively. Vm is the peak value of the stator voltage. ω is the synchronous speed in rad/sec. The stator voltages in the 'abc' axes Vabc is transferred to the d, q axes Vqd0 by using park's transformation.

The transformation matrix Ks is given by equation

$$K_s = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{0s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (14)$$

III. CLOSED LOOP SPEED CONTROL OF PMSM:

A. Vector Control scheme for closed loop PMSM drive:

The block diagram of the closed loop control scheme is shown in Fig. 3. The constant torque method of vector control scheme has been considered for analysis. In this method, the angle between the rotor field and stator current phasor is known as torque angle and is maintained at 900 so that flux is kept constant, then the torque is controlled by the stator current magnitude [1].

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The machine, speed and position feedback, speed and current controllers, and inverter constitute the PMSM drive. The error between the reference and actual speed has given as the input to the speed controller, which generates the torque reference and is proportional to I K t q by substituting id =0, equation (25) and (26) is obtained.

$$T \; = K_t \, i_{qs}^{e} \qquad (15)$$

$$K_t = \frac{3}{2}\frac{P}{2}\lambda_{af} \qquad (16)$$

The stator current iqd0 in the d, q axes is transferred to the 'abc' axes by using Inverse Park's transformation given by equation (17)

$$i_{abcs} = K_s^{-1}\, i_{qd0s} \qquad (17)$$

$$K_s^{-1} = \frac{2}{3}\begin{bmatrix} \cos\theta & \sin\theta & \frac{1}{2} \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & \frac{1}{2} \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & \frac{1}{2} \end{bmatrix} \qquad (18)$$

The reference current ias,ibsandics are generated by substituting equation (28) in equation (27) In the constant air gap flux mode of operation, Kt is constant up to base speed and is equal to unity. Hence, the torque reference is directly proportional to I q , which is transformed to 'abc' axes by using Inverse Park's transformation given by equations (27). The 'dq0 to abc' transformation block shown in Fig. 3 gives the stator reference current ia, ib and ic in 'abc' axes which is compared with the actual current and the current error is given to a hysteresis controller. The hysteresis current controller generates triggering pulses to the inverter in such a way that the actual current follows the reference current.

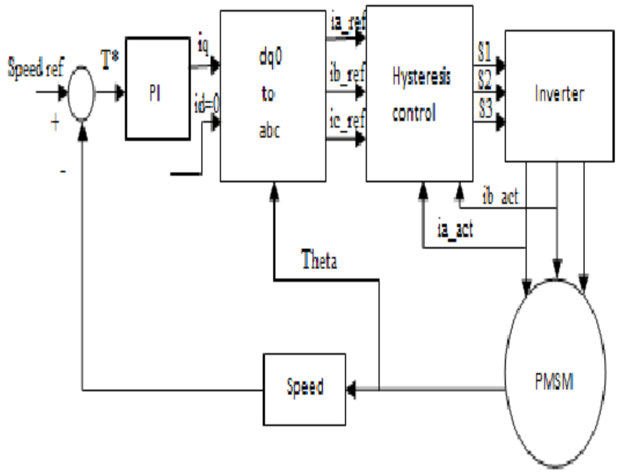

Fig. 3.Block Diagram of Closed Loop Speed Control of PMSM

B.Developed simulation Model of closed loop speed controlof PMSM Drive Implemented in Matlab/Simulink:

The three phase voltage output of Pulse width modulated (PWM) voltage source inverter (VSI) is given by equations

(28) to (30).
Van □□Vdc (S1 −□S4) (28)
Vbn□□Vdc (S3 −□S6) (29)
Vcn□□Vdc (S5 −□S2) (30)
S1−□S6 are three phase inverter switches.

The mathematical model of the PMSM expressed by equations (1) to (24) along with the mathematical model of three phase VSI with a hysteresis current controller has been utilized in implementing the closed loop vector control scheme of complete PMSM drive in Matlab. The developed system simulation model of PMSM drive system in Matlab\simulinkis shown in Fig. 4. The subsystem for the mathematical mode of PMSM alone is shown in Fig. 5.

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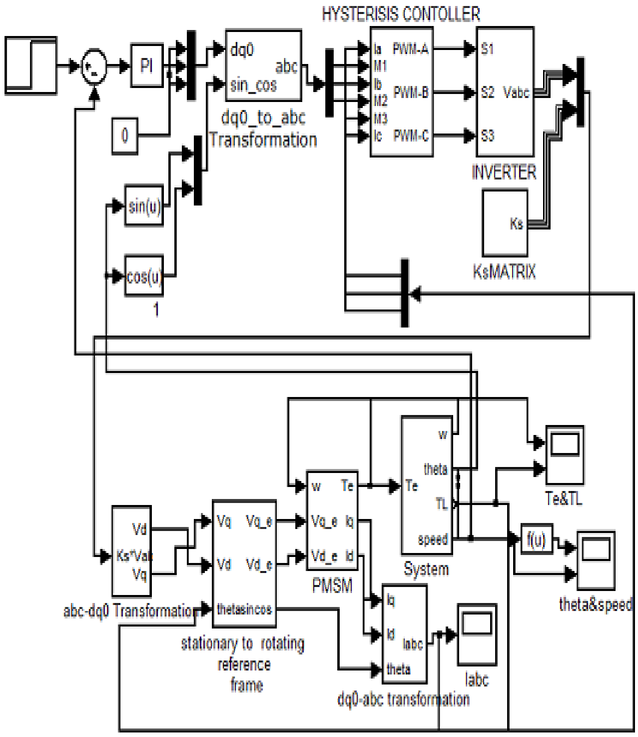

Fig. 4. Developed simulation Model of closed loop PMSM drive implemented in Matlab

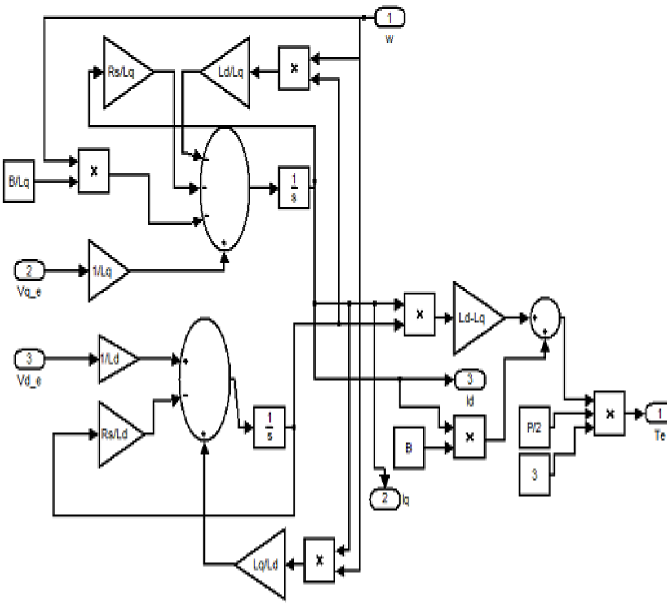

Fig. 5.Mathematical Model of PMSM implemented in Matlab

C. Hysteresis current controller of VSI:

The PWM pulses for the three phase VSI are generated using a hysteresis current controller, which accepts the current error as input. The subsystem of hysteresis controller implemented in Matlab is shown in Fig. 6.

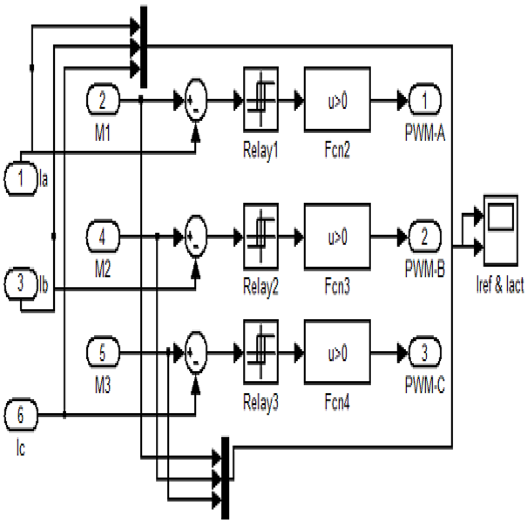

Fig. 6.Simulation block diagram of Hysteresis controller in Matlab\simulink

The closed loop PMSM drive has also been implemented by circuit simulation using the existing library blocks in order to validate the developed simulation model as shown in fig. 7.

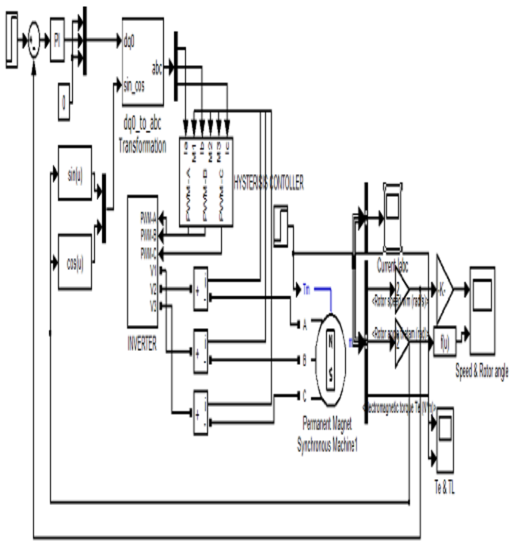

Fig. 7. Circuit Simulation Model of PMSM using Matlab Simulink

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IV. Simulation Results:

The motor parameters are Rs=18.7Ω, Ld & Lq=0.02682, J=2.26e-5kgm2, F=1.349e-5Nm/rad/s, P=2,Freq=50HZ,Vdc=300, B=0.1717V/rad/s, For constant speed operation, the reference speed is set as 3000 rpm and the load torque varied from 0.6N-m to 0.8N-m at 0.25sec. Fig 8 to fig 17 shows the simulation results of the developed model and the circuit simulation model for different conditions with PI controller which includes, speed,torque and current responses along with THD analysis. Fig. 18 and 27 shows the responses of the developed system simulation model and the circuit simulation model with Fuzzy controller.

For constant torque operation the load torque is kept at 0.8 Nm and the reference speed is varied from 1500rpm to 3000rpm at 0.25 sec. The simulation results of the developed system simulation model and the circuit simulation model is shown in fig 10 and fig 14 respectively. Fig. 18 and 20 shows the circuit simulation model andthe stator current response of the developed model respectively. It can be observed the stator current frequency increases for a increased reference speed.

Since it is a constant torque operation mode, the current magnitude remains constant for the entire duration. It can be observed from fig 14 and fig 19, the simulation results shows that transient response is improved with fuzzy compared to PI controller.it shows the accuracy of the developed model, but the computation time of the developed model is normally very less when compared to the circuit simulation done by any simulation softwares.

Case-1: Simulation results of developed model for constant speed and variable torque using PI controller.

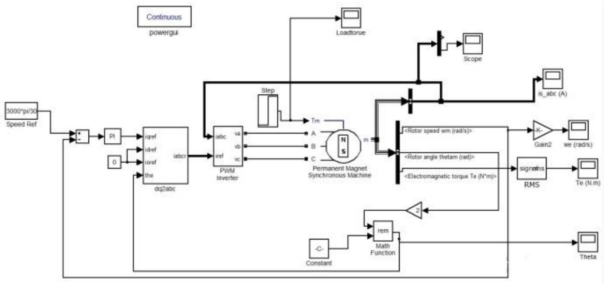

Fig.8 Matlab/Simulink model of physical model for constant speed and variable torque using PI controller

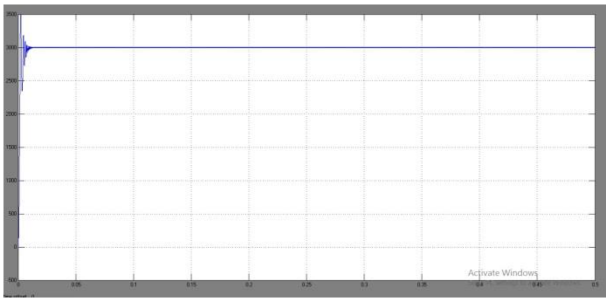

Fig.9 simulation waveform of PMSM drivespeed

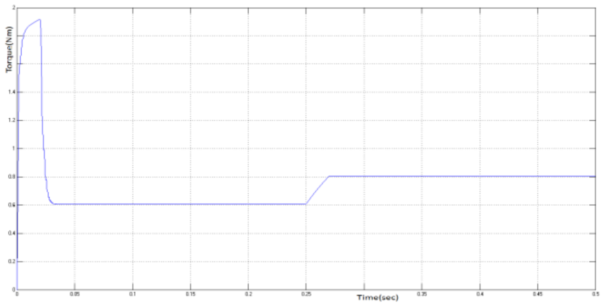

Fig.10 simulation waveform of electromagnetic torque

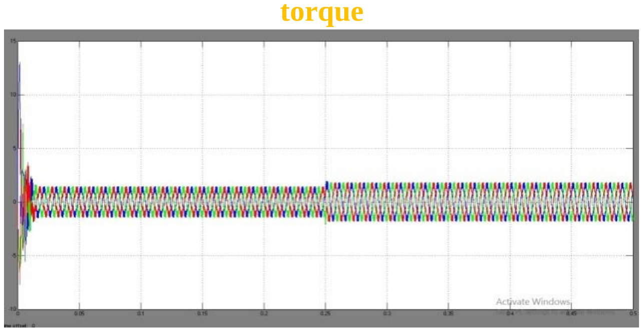

Fig.11 simulation waveform of currents of 3 phases of VSI

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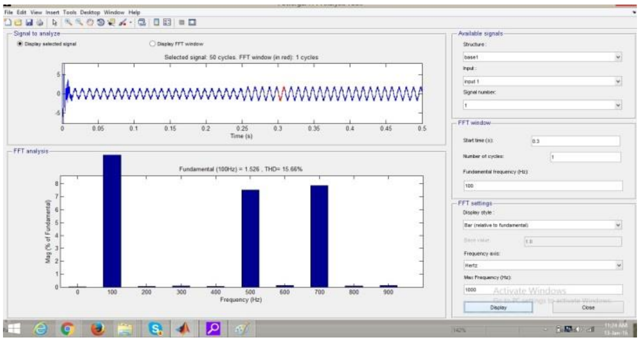

Fig.12 THD of PMSM drive using PI controller

Case-2: Simulation results of developed model for variable speedand constant torque using PI controller

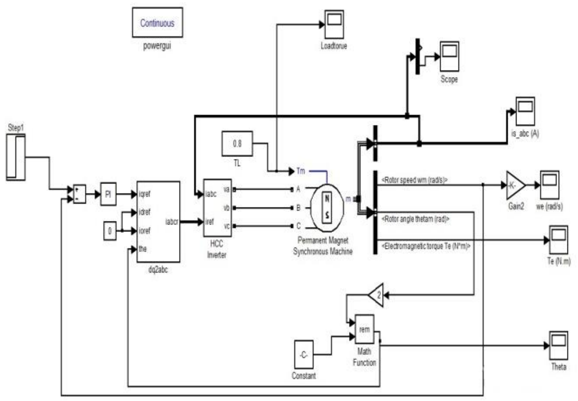

Fig.13 Matlab/Simulink model of physical model for constant torque and variable speed using PI controller

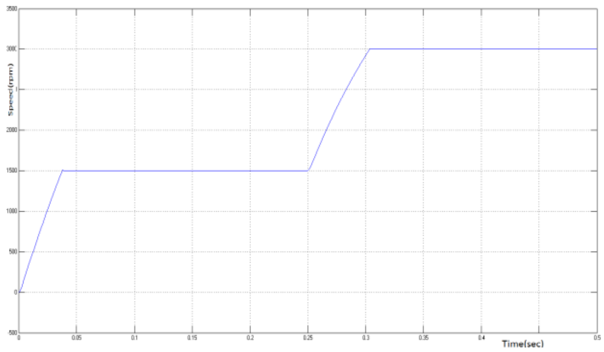

Fig.14 simulation waveform of PMSM drive speed

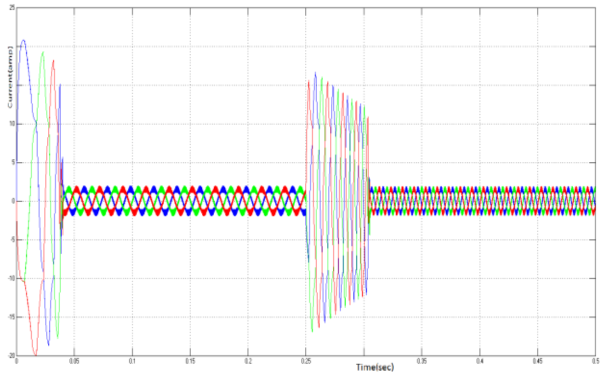

Fig.15 simulation waveform of currents of VSI

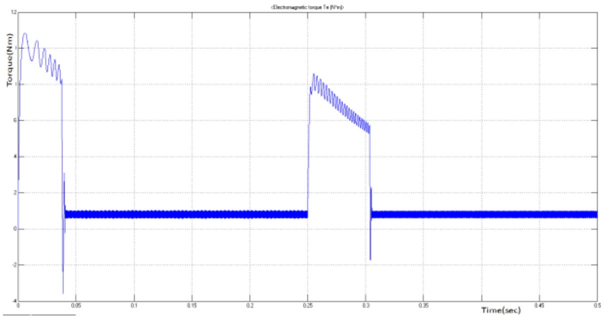

Fig.16 simulation waveform of electromagnetic torque

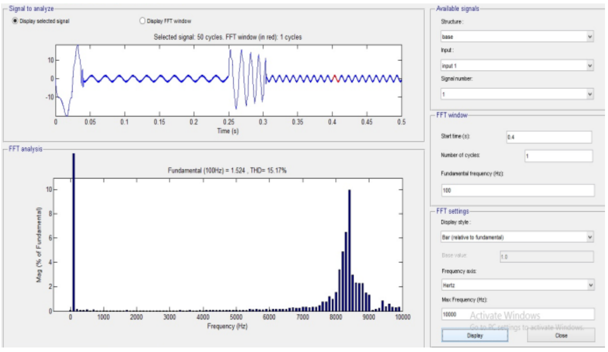

Fig.17 THD analysis of PMSM drive

Case-3: Simulation results of developed model for variable speed and constant torque using FUZZY controller

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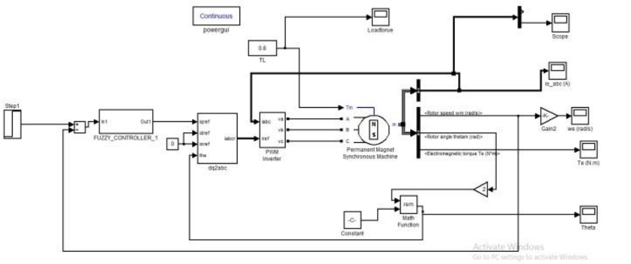

Fig.18 Matlab/Simulink model of physical model for constant torque and variable speed using FUZZY controller

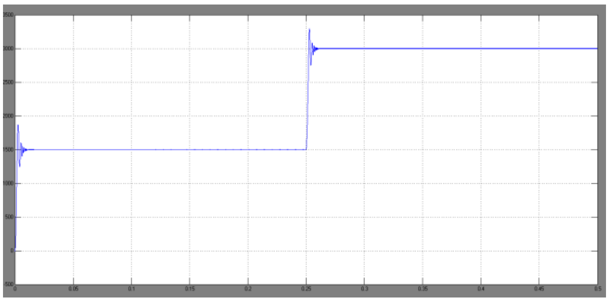

Fig.19 simulation waveform of speed

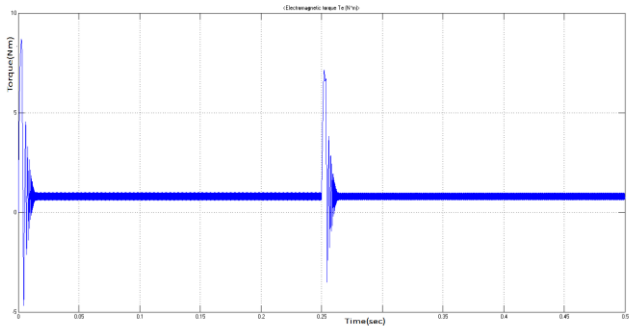

Fig.20 simulation waveform of electromagnetic torque

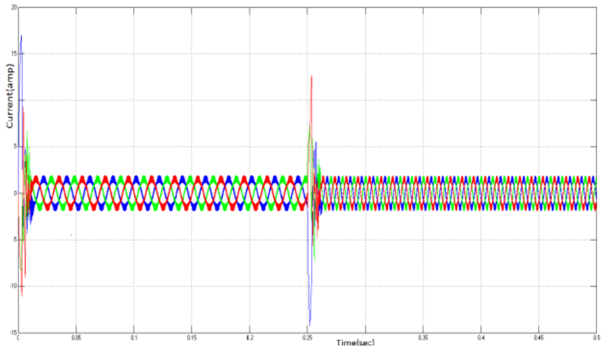

Fig.21 simulation waveform of currents of VSI

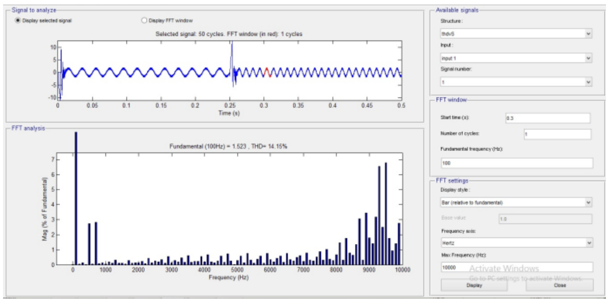

Fig.22 THD analysis of PMSM drive

Case-4: Simulation results of developed model for constant speed and variable torque using FUZZY controller

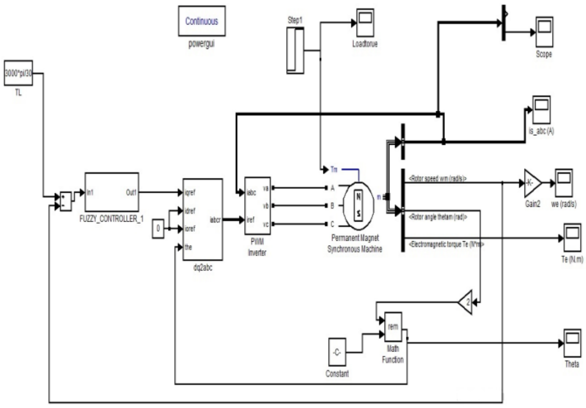

Fig.23Matlab/Simulink model of physical model for constant speed and variable torque using FUZZY controller

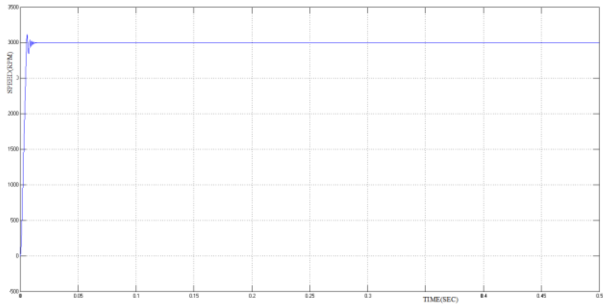

Fig.24 simulation waveform of variable speed

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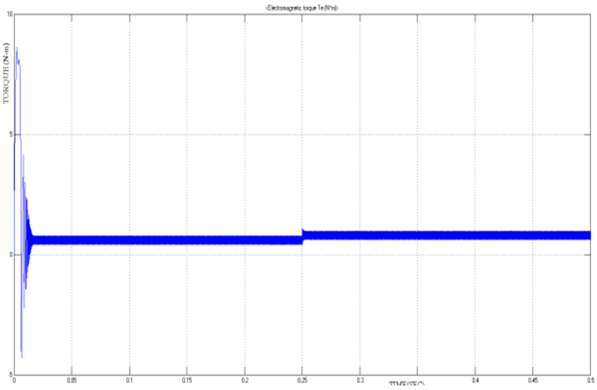

Fig.25 simulation waveform of electromagnetic torque

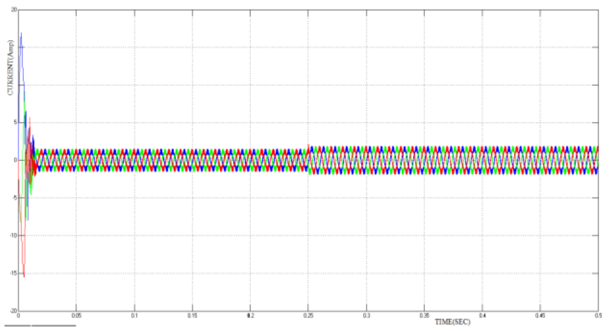

Fig.26 simulation waveform of currents of VSI

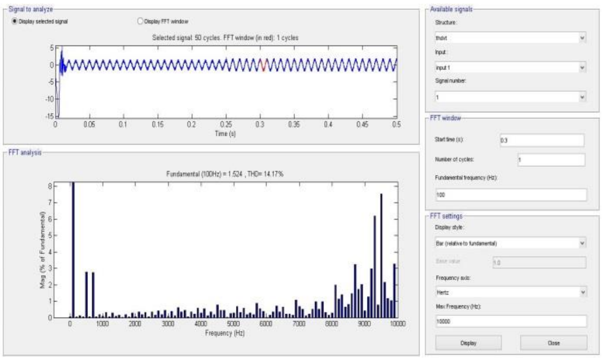

Fig.27 THD analysis of PMSM drive

V .Conclusion:

An advanced simulation model of closed loop PMSM drive system has been developed by utilizing the fuzzy controller and hysteresis controlled three phase VSI inverter. .Various simulation results are analyzed and presented on PMSM drive for different conditions in order to demonstrate the satisfactory performance. From the simulation results of closed loop PMSM drive using PI and FUZZY control technique. FUZZY control technique responds very fast to the changes in systems and gives the required output i.e dynamic and transient response improved with fuzzy controller compared to PI controller ,at the same time THD also reduced with FUZZY controller. So from analysis FUZZY control technique is best one compared to PI controller in measuring of transient response, harmonics and time taken to computation.

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