Design and Simulation of Multilevel Inverter Fed PMSM

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Abstract

A robust controller which is designed by employing variable-structure control is presented for a permanent-magnet synchronous motor (PMSM) position control system. It is to achieve accurate control performance in the presence of plant parameter variation and load disturbance. In addition, it possesses the design flexibility of the conventional state feedback control. It is applied to the position control of a PMSM. Simulation results show that the proposed approach gives a better position response and is robust to parameter variations and load disturbance. The simulation results based on Matlab/Simulink are discussed in detail in this paper.

1. INTRODUCTION

In recent years, advancements in magnetic materials, semiconductor power drives, and control theories have made the permanent-magnet synchronous motor (PMSM) drive play a vitally important role in motion-control applications in the low-to-medium-power range. The desired features of the PMSM include its compact structure, high air-gap flux density, high power density, high torque-to-inertia ratio, and high torque capability. When compared with an induction servo motor, a PMSM also has many advantages. For instance, it has the higher efficiency, resulting from the absence of rotor losses and lower no-load current below the rated speed. In addition, its decoupling control performance is far less sensitive to the parameter variations of the motor [1]. To achieve fast four-quadrant operation, smooth starting, and acceleration, the field-oriented control, or vector control, is used in the design of the PMSM drive. Much research has devoted fresh attention to the control of the PMSM [1]–[4], [6]. From the designer's viewpoint, linear state feedback control is theoretically an attractive method for controlling a linear plant represented by a state-space model. The method has the full flexibility of shaping the dynamics of the closed-loop system to meet the desired specification. Techniques such as pole placement or linear-quadratic (LQ) method can be used to achieve the designed goals. The motor system usually can be modeled as a second-order state-space system in which the mechanical velocity and position are used as the system states. Thus, these methods, pole placement and LQ method seem quite suitable to the motor drive system. There are, however, few real motor systems adopting these methods as the controller design. The main problem is that, while the desired performance can be achieved in the nominal system, it is difficult to incorporate robustness consideration into the design procedure. Considering the optimal control, the LQ method is an easy way to decide the demand control law to satisfy the requirements. It is based on the state-space model. To find the control law, a relative Riccati equation is first solved, and an optimal feedback gain, which will lead to optimal results evaluating from the defined performance index, is obtained. Besides the facts, once the external disturbance and/or the parameters uncertainty exist, then the desired responses may not be obtained. Thus, if one wants to develop an effective optimal control strategy for the position control of the PMSM drive, one has to overcome the drawbacks mentioned above, including the problems of robustness and keeping the designed flexibility of the pole placement and LQ method. In the past decade, the variable-structure control (VSC) or sliding-mode control (SMC) strategies have been the focus of many studies and much research, such as in PM synchronous servomotor drive control [2], electro hydraulic position servo control [5], optimal PMSM control [6], and induction motor servo drive control [7], [8]. It is

known that the VSC can offer such properties as insensitivity to parameters variations,
external disturbance rejection and fast dynamic response.

Generally, to design a conventional SMC system, there are two design phases that must be considered, namely, the reaching phase and sliding phase. The robustness of a VSC system resides in its sliding phase, but not in its reaching phase. In other words, the closed-loop system dynamic is not completely robust all the time. In addition, while the design technique for the sliding mode has been well established, there is no easy way to shape the dynamics of the reaching phase. Thus, the optimal problem considered in [5] and [6] is weak in the reaching phase and the performance designing. The proposed optimal control scheme is to meet all the requirements and solve the drawbacks mentioned above. It is designed by combining the LQ method and the VSC method. LQ method is used to decide the demand feedback gain to shape the dynamics and to meet the requirement of the performance index. At the same time, a new VSC strategy is used to conserve the robustness in the optimal control scheme. The system controlled by this VSC strategy will guarantee the robustness for the PMSM position control system.

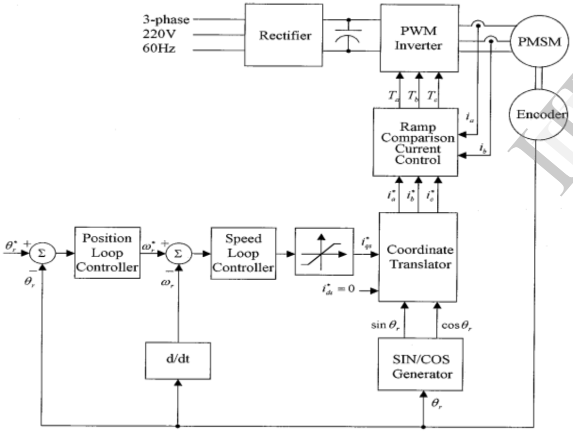

Fig. 1. System configuration of field-oriented synchronous motor

2. PMSM MATHEMATICAL MODEL

Neglecting the influences of hysteresis and eddy current losses under the conditions of no saturant magnetic circuit and sinusoidal magnetic field distribution, the state space equation of Field-Oriented PMSM in a synchronous rotating reference frame (d-q) is described as follow [9]:

$$\begin{bmatrix} i_d' \\ i_q' \\ \omega' \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & p\omega & 0 \\ -p\omega & -\frac{R}{L_q} & -p\frac{\psi_f}{L_q} \\ 0 & p\frac{\psi_f}{J_m} & -\frac{B_m}{J_m} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{U_d}{L_d} \\ \frac{Uq}{L_q} \\ -\frac{T_l}{J_m} \end{bmatrix} \tag{1}$$

Where R: coil equivalent resistance (Ω)
L_d, L_q: d-axis and q-axis equivalent inductance (H)
L_d: equivalent inductance (H)
P: motor pole magnetic pairs
ω: rotor angular velocity (rad/s)
Ψ_f: flux per pole (Wb)
T_l: the total load on the motor shaft (N□m)
i_d , i_q : d-axis and q-axis current component (A)
J_m: the total rotational inertia of motor shaft (kg-m2)

According to Vector Control, the synthesis vector (i_s) of three-phase stator current is always controlled to locate at the q-axis, and perpendicular to the rotor flux vector. That is $i_q = i$, $i_d = 0$. So the model of PMSM can be changed into a mathematical model of DC motor. Let DC component $i_q=i_s=I$, the equation(1) can be transformed as:

$$\begin{bmatrix} \frac{dI}{dt} \\ \frac{d\omega}{dt} \\ \frac{d\theta}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_q} & -p\frac{\psi_f}{L_q} & 0 \\ p\frac{\psi_f}{J_m} & -\frac{B_m}{J_m} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I \\ \omega \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{U_q}{L_q} \\ -\frac{T_l}{J_m} \\ 0 \end{bmatrix} \tag{2}$$

Where ω is rotor angular velocity and θ is position angle.
From the equation (2), the State space equation of PMSM servo system can be simplified as:

$$\begin{cases} X' = AX + BI + DT_f \\ Y = HX \end{cases} \tag{3}$$

Where

$$X=\begin{bmatrix}\omega\\ \theta\end{bmatrix},\quad A=\begin{bmatrix}-\frac{B_m}{J_m} & 0\\ 1 & 0\end{bmatrix},\quad B=\begin{bmatrix}p\frac{\psi_f}{J_m}\\ 0\end{bmatrix}$$

Y is the output variables and

$$Y=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}\omega\\ \theta\end{bmatrix} \tag{4}$$

3. DESIGN OF VARIABLE STRUCTURE CONTROLLERS

Let the input reference for speed and position angle as:

$$R(t)=[\omega^*(t) \quad \theta^*(t)] \tag{5}$$

It represents the performance requirements during the startup, the stable operation and the brake of motor. The tracking error vector is defined as:

$$E(t)=Y(t)-R(t) \tag{6}$$

According to the control objective ($E(t)=0$), the Switching
function is designed as follow:

$$S(t)=CE(t) \tag{7}$$

Where C= [C1 C2] and C1>0, C2>0
From the equation (6) and (7), the following formula can be derived.

$$S'(t)=CE'(t)=C(Y'(t)-R'(t))$$
$$=C\times[HAX+HBI+HDT_l-R'] \tag{8}$$

The sign of $S(t)$ can be determined by the equation(7).

Under the reaching condition of Variable structure control (S(t)XS'(t) <0) the sign of S'(t) can be derived. So the range of the control variable(I) can be determined by the equation(8), which can ensure the system meet the reaching condition of variable structure control. In addition, the chattering along the switching surface is a fatal weakness to variable structure control, which will debase the control performances and bring the machine wear, some energy loss and other adverse effects. In order to reduce the chattering, the exponential reaching law is applied as follow:

$$S'=\varepsilon\times\operatorname{sgn}(S)-K\times S \tag{9}$$

Where $\varepsilon > 0, K > 0$

From the equation (8) and (9), the control variable (I) can be deduced as:

$$I=[CHB]^{-1}\times[CR'-CHDT_l-CHAX+\varepsilon\operatorname{sgn}(S)-KS] \tag{10}$$

4. DESIGN OF LOAD OBERSERVER

From the equation (10), the control variable (I) couldn't be determined if the state variable(X) and the load torque (T_l) is not be known. In practice, the state variable X is easy to measure, but the load torque T_l is not. In order to solve this problem, an asymptotic observer is designed to observe the load torque (T_l) indirectly. A novel Luenberger load observer is designed as:

$$\frac{d\hat{T}}{dt}=\frac{n}{J}[-\hat{T}+(n-B_m)\omega+p\psi_f I \tag{11}$$

Where n is a design parameter and n>0, and $\hat{T}$ is the estimation of T ($T=T_l+ n\,\omega_m$). Suppose load is constant or slowly changing, the derivative of the load torque (T_l) is approximately equal to zero, that is $T_l'=0$.

ΔT is the estimation error, that is $\Delta T = T - \bar{T}$. From the equation (2), the following equation can be derived.

$$\frac{d(\Delta T)}{dt}=\frac{d(T_l+n\omega)}{dt}-\frac{d\hat{T}}{dt}=-\frac{n}{J_m}\Delta T \tag{12}$$

So

$$\Delta T=C_0\exp(-\tfrac{n}{J_m}) \tag{13}$$

Where C_0 is a constant.
For $n>0$, the equation (14) can be deduced.

$$\lim_{t\to\infty}\Delta T=0 \tag{14}$$

From the above equation, it is evident that the load torque (T_l) can be estimated by $\hat{T}$- nω. Figure 2 is a control scheme of the PMSM variable structure servo system, in which the algorithm of vector calculator is given by the following equation.

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \sqrt{2/3}\cdot i_S \cdot \begin{bmatrix} \cos(\theta+90^\circ) \\ \cos(\theta+90^\circ-120^\circ) \\ \cos(\theta+90^\circ+120^\circ) \end{bmatrix} \qquad (15)$$

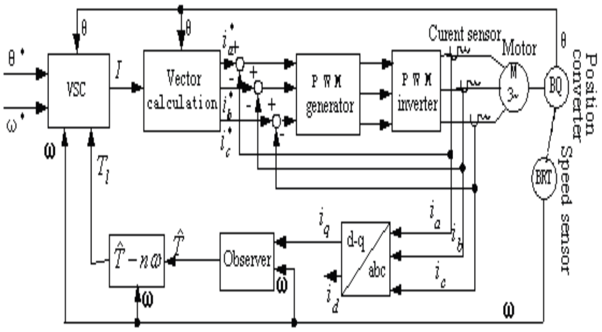

Fig: 2. Control scheme of the PMSM variable structure servo system

5. MULTILEVEL INVERTER

As previously mentioned, three different major multilevel converter structures have been applied in industrial applications: cascaded H-bridges converter with separate dc sources, diode clamped, and flying capacitors. Before continuing discussion in this topic, it should be noted that the term multilevel converter is utilized to refer to a power electronic circuit that could operate in an inverter or rectifier mode. The multilevel inverter structures are the focus of in this chapter; however, the illustrated structures can be implemented for rectifying operation as well.

5.1. Cascaded Multi Level Inverters:

A different converter topology is introduced here, which is based on the series connection of single-phase inverters with separate dc sources. The power circuit for one phase leg of a nine-level inverter with four cells in each phase. The resulting phase voltage is synthesized by the addition of the voltages generated by the different cells. Each single-phase full-bridge inverter generates three voltages at the output:+Vdc,0 and –Vdc. This is made possible by connecting the capacitors sequentially to the ac side via the four power switches. The resulting output ac voltage swings from -4Vdc to +4Vdc with nine levels, and the stair case waveform is nearly sinusoidal, even without filtering.
Another version of cascaded multilevel inverters using standard three-phase two-level inverters has recently been proposed. It uses an output transformer to add the different voltages. In order for the inverter output voltages to be added up, the inverter outputs of the three modules need to be synchronized with a separation of 120 between each phase. For example, obtaining a three-level voltage between outputs *a* and *b*, the voltage is synthesized by Vab=Va1-b1+Vb1-a2+Va2-b2. The phase between b1and a2 is provided by and through an isolated transformer. With three inverters synchronized, the voltages Va1-b1,Vb1-a2,Va2-b2 are all in phase; thus, the output level is simply tripled.

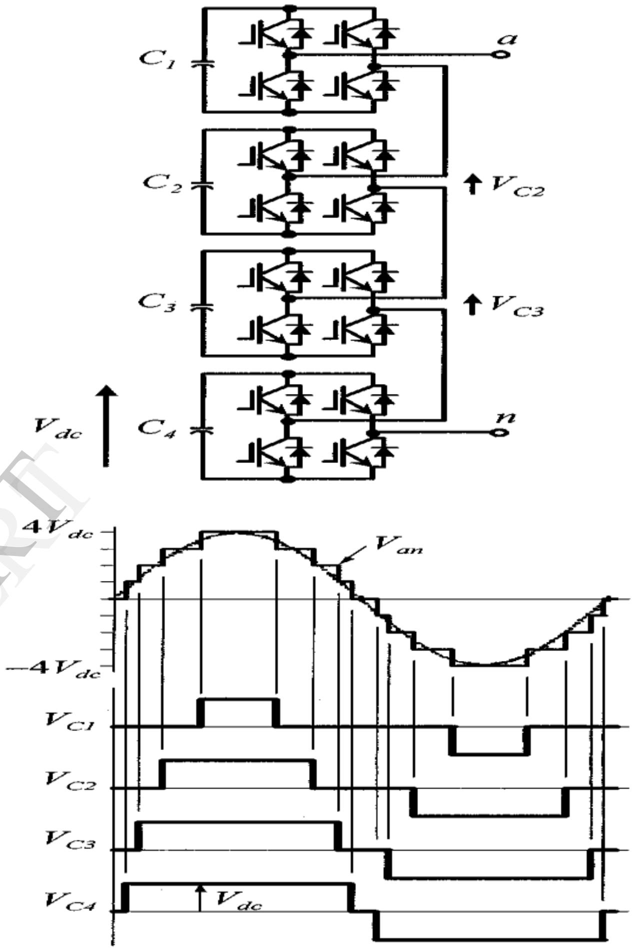

Fig: 3. Cascaded inverter circuit topology and its associated waveform

To achieve a high-quality output voltage waveform, the voltages across all of the dc capacitors should maintain a constant value. Since there are multiple possible switching states that can be used to synthesize a given voltage level, the particular switching topology is chosen such that the capacitors with the lowest voltages are charged or conversely, the capacitors with the highest voltages are discharged. This redundant state selection approach is used to maintain the total dc link voltage to a near constant value and each individual cell capacitor within a tight bound. Different pulse width modulation (PWM) techniques have been used to obtain the multilevel converter output voltage. One common pulse width modulation (PWM) approach is the phase shift PWM (PSPWM) switching concept.

Fig: 4. Eleven-level cascaded multilevel Converter

6. MATLAB MODELING AND SIMULATION RESULTS

As angular velocity and position angle constraint relation exists, the reference value is given by either angular velocity or position angle. Here simulation is carried out in different cases 1). Proposed PMSM Variable Structure Servo System 2). Proposed PMSM Variable Structure Servo System using Multilevel Converter Topology

Case 1: Proposed PMSM Variable Structure Servo System

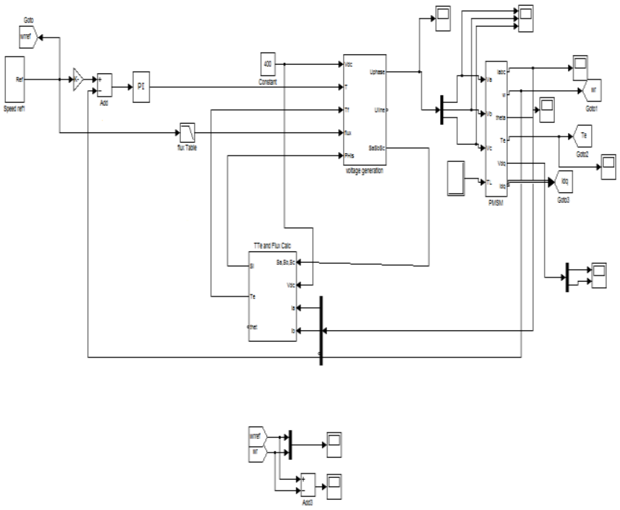

Fig.5 Matlab/Simulink Model of Proposed PMSM Variable Structure Servo System

Fig.5 shows the Matlab/Simulink Model of Proposed PMSM Variable Structure Servo System using Matlab/Simulink Platform.

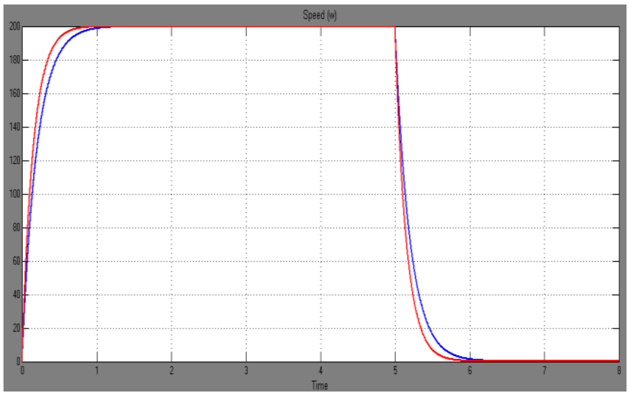

Fig.6 Tracking Curve of the speed, Ref Speed & Actual Speed

Fig.6 shows the Tracking Curve of the speed, Ref Speed & Actual Speed of Proposed PMSM Variable Structure Servo System.

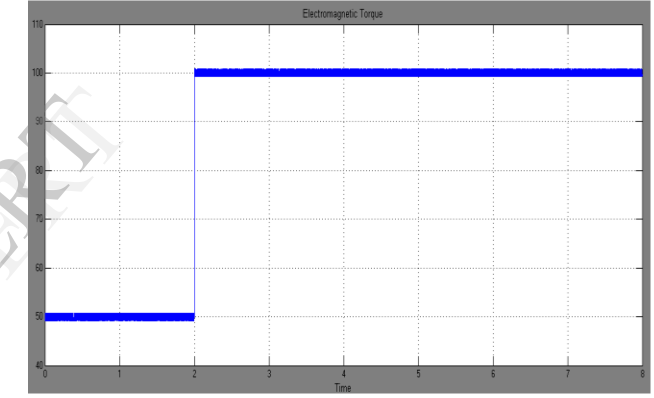

Fig.7 Electromagnetic Torque

Fig.7 shows the Electromagnetic Torque of Proposed PMSM Variable Structure Servo System.

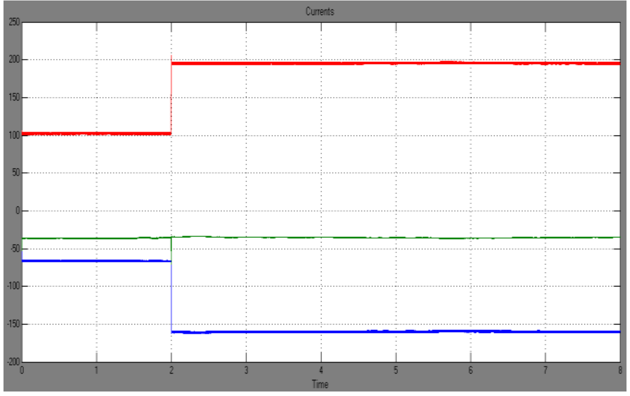

Fig.8 Stator Currents

Fig.8 shows the Stator Currents of Proposed PMSM Variable Structure Servo System.

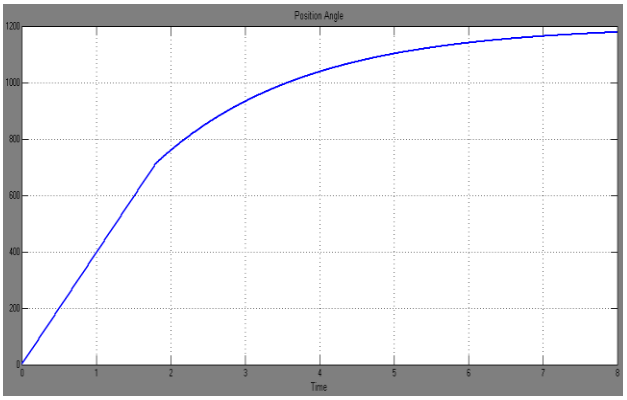

Fig.9 Tracking Curve of Position Angle

Fig.9 shows the Tracking Curve of Position Angle of Proposed PMSM Variable Structure Servo System.

Case 2: Proposed PMSM Variable Structure Servo System using Multilevel Converter Topology

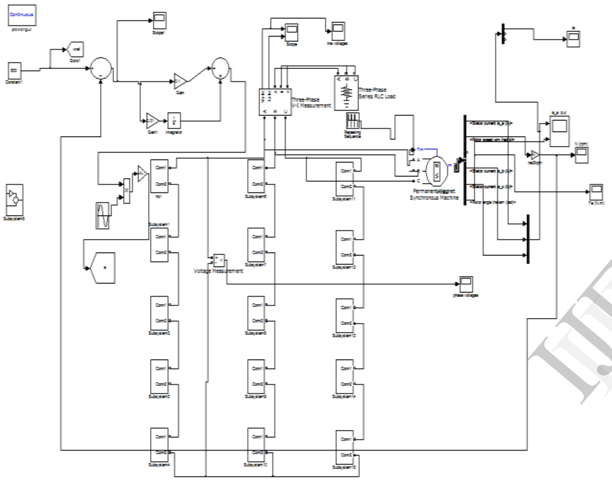

Fig.10 Matlab/Simulink Model of Proposed PMSM Variable Structure Servo System using Multilevel Converter Topology

Fig.10 shows the Matlab/Simulink Model of Proposed PMSM Variable Structure Servo System with Multilevel Converter Topology using Matlab/Simulink Platform.

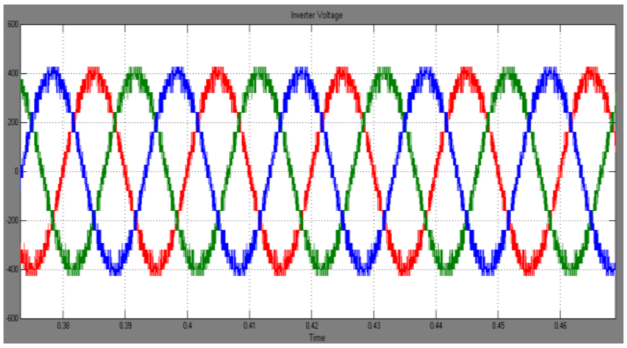

Fig.11 Inverter Output Voltage

Fig.11 shows the Inverter Output Voltage of Proposed PMSM Variable Structure Servo System with Multilevel Converter Topology.

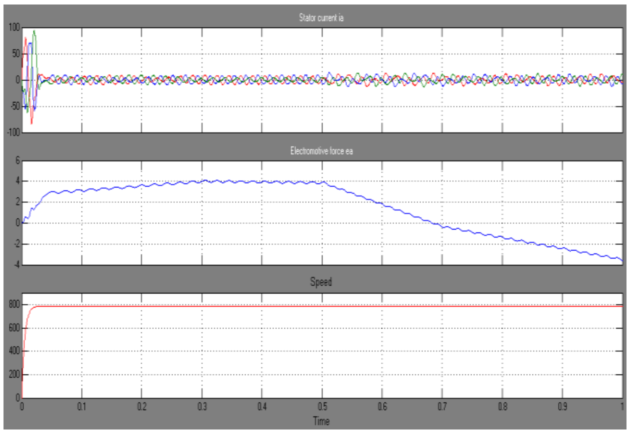

Fig.12 Stator Current, Electromagnetic Torque, Speed

Fig.12 Stator Current, Electromagnetic Torque, Speed of Proposed PMSM Variable Structure Servo System with Multilevel Converter Topology.

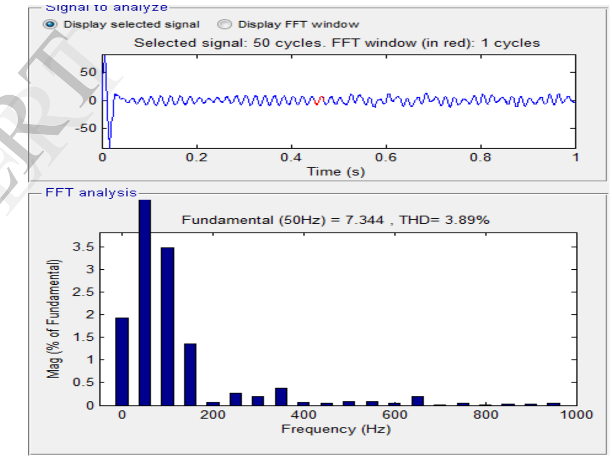

Fig.13 FFT Analysis of Phase A Stator Current

Fig.13 FFT Analysis of Phase A Stator Current of Proposed PMSM Variable Structure Servo System with Multilevel Converter Topology, we get 3.89%.

7. CONCLUSION

Multilevel inverters which have a high number of components. This is a subject of increasing importance I high-power inverters. Advantages of this multilevel approach include good power quality, good electromagnetic compatibility (EMC), low switching losses, and high voltage capability. Here we proposed 11 Level multilevel cascaded converters has been implemented, levels increases we get better response as well as better THD values with respect to IEEE standards. In this paper, variable structure control theory is applied to analysis of permanent magnet synchronous motor servo system and a new variable structure controller based on rotor flux oriented vector control methods is presented, which is simple and practical. Some results of simulation experiments indicate that PMSM servo system controlled by the proposed controller has speedy response, high accuracy and strong robustness against its parameter variations and load disturbances. Its performance is much better than that of traditional control methods.

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