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Fractional Order Speed Control of Three Level Inverter Fed PMSM System Using Sliding-Mode Observer

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ABSTRACT*:* This paper addresses the performance of a permanent magnet synchronous motor (PMSM) speed control system which is driven by a multilevel inverter. A three level inverter is used as the power source for the system which will reduce the winding stresses due to harmonics during the motor operation. A new sliding mode observer based on sigmoid function as switching function is used for estimating the speed and position of PMSM which has the capability to reduce the chattering phenomenon and to make the system more insensitive to disturbances. A fractional order PI controller is used as the speed controller for the system in addition to the two PI controllers that are used as the inner current controllers. Simulation and experimental results can be a testament for the effectiveness of the proposed technique.

KEYWORDS*:* PMSM, Three Level Inverter, Sliding Mode Observer (SMO), Sigmoid function, Fractional Order PI controller.

I. INTRODUCTION

PMSMs are a special type of synchronous motors that are being required in various applications. These motors are available in wide power ranges, ranging from 0.37kW to around 30kW. And it can give an efficiency of about 81-88% [1].

Field Oriented Control employed in the system helps to achieve independent control over flux and torque of the machine. Based on the closed loop control of speed and current, the simulation model of the surface-mounted PMSM (SPMSM) vector control system with a three level inverter with its corresponding Space Vector Pulse Width Modulation (SVPWM) method was proposed. A sliding mode observer was developed for estimation of speed and position. In this work, the signum function of normal SMO is replaced by a sigmoid function which will give a smooth variation during the switching rather than a sudden one. In this study a FOPI speed controller is applied to a PMSM speed control system based on field oriented control. There are not many works dealing with a PMSM field oriented control driven by a multilevel inverter and that too operating under a sensorless technique based on a new and improved sliding mode observer. The tuning of such a PI controller will be done after considering all the parameters of the system such as inverter delays, motor time constants, delay introduce by Sliding Mode Observers and all the other delays that can prove to be a problem while tuning the controller.

II. PMSM MODELLING

According to the theory of AC motors, the mathematical model of the PMSM is developed according to the generalized theory of machines as follows [2]-[3]:

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$$V_q = R_s i_q + \omega_r \lambda_d + \frac{d\lambda_q}{dt} \qquad (1)$$

$$V_d = R_s i_d - \omega_r \lambda_q + \frac{d\lambda_d}{dt} \qquad (2)$$

where,R_s is the stator resistance, ω_r is the electrical rotor speed, V_d&V_q are d and q axis voltages respectively. Similarly i_d&i_q are d and q axis currents respectively. λ_d & λ_q are the flux linkages given by,

$$\lambda_q = L_q i_q \qquad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \qquad (4)$$

where L_q&L_d are and d axis inductances respectively. λ_f is the flux linkage between magnetic field of the permanent magnet and the stator windings.

The equation for electromagnetic torque for a PMSM is given by

$$T_e = \frac{3P}{4}\left[\lambda_d i_q - \lambda_q i_d\right] \qquad (5)$$

where P is the number of poles.

III. THREE LEVEL INVERTER

A multilevel inverter is used as the power source for driving PMSM. In comparison to ordinary two level three leg inverters, the multilevel inverters can give better performance in the aspect of reduction in harmonic stresses on the winding and hence reduction in heating up of the winding [4]. Also the switches that are required can be of small dv/dt ratings as the switches are subjected to relatively small changes in voltages. By providing intelligent power modules the reliability of the power converter can be improved. It will give better electrical performance. However, as the number of switches is increased the complexity of the system will also increase but it will get justified if its performance and advantages are considered. The switching strategy based on SVPWM is employed for driving this inverter.

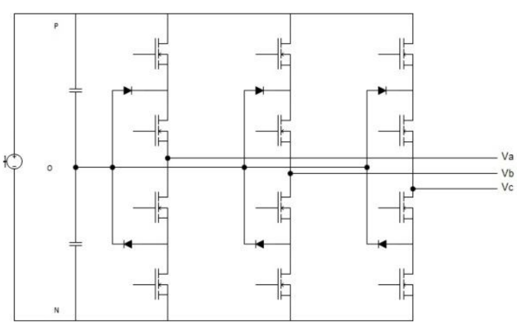

Fig. 1 Three Level Inverter Model

A neutral point clamped three level inverter [4] is used in this work which is shown in Fig.No.1. MOSFET switches with antiparallel diodes are used. Two almost identical capacitors are required for dividing the voltage evenly. As compared to two level inverters, three level inverters have smaller output voltage steps that mitigate motor issues due to long power cables between the inverter and the motor. These issues include surge voltages and rate of voltage rise at the motor terminals and motor shaft bearing currents. In addition, the cleaner output waveform provides an effective switching frequency twice that of the actual switching frequency [4]. If an output filter is required, the components will be smaller and less costly than for an equivalent two level inverter. But the switching strategy for such a converter will be a little bit complex. So a 3 level space vector pulse width modulation technique is employed for developing the control signals for the switches.

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IV. SLIDING MODE OBSERVER

The sliding mode observer has its base on the variable structure theory [5]. In order to design a sliding mode observer, first a sliding surface has to be defined. The sliding surface selected for the present work is shown as,

$$S(x) = \hat{i}_s - i_s \qquad (8)$$

where $\hat{i}_s = [\hat{i}_\alpha \quad \hat{i}_\beta]^T$ is the estimated value of current and $i_s = [i_\alpha \quad i_\beta]^T$ is its measured value.

With reference to the mathematical model of PMSM in the stationary reference frame, the equations governing sliding mode observer is expressed as follows,

$$L_s\left(\frac{d\hat{i}_\alpha}{dt}\right) = -R_s\hat{i}_\alpha + u_\alpha - kF(\hat{i}_\alpha - i_\alpha) \qquad (9)$$

$$L_s\left(\frac{d\hat{i}_\beta}{dt}\right) = -R_s\hat{i}_\beta + u_\beta - kF(\hat{i}_\beta - i_\beta) \qquad (10)$$

$$F(x) = \left[\frac{2}{(1+e^{-ax})}\right] - 1 \qquad (11)$$

where 'a' is an adjustable parameter & k is the observer gain. As sigmoid function is employed here [5], the switching between 0 and 1 will be smooth so that the effect of chattering will be very less and hence the requirement of a low pass filter at
the output and its phase angle compensation requirement can be avoided.

Speed and position of the rotor can be estimated with the help of this observer. The output of this sliding mode observer will be back emfs of the machine in the stationary reference frame. This can be employed to estimate the speed and position as follows,

$$\omega_r = \frac{\sqrt{e_\alpha^{\;2} + e_\beta^{\;2}}}{\lambda_f} \qquad (12)$$

V. FRACTIONAL ORDER PI CONTROLLER

The fractional calculus operator is given as follows [6]-[7]:

$${}_aD_t^{\alpha} = \frac{d^\alpha}{dt^\alpha}, \mathrm{Re}(\alpha) > 0 \qquad (13)$$

$${}_aD_t^{\alpha} = 1, \mathrm{Re}(\alpha) = 0 \qquad (14)$$

$${}_aD_t^{\alpha} = \int_\alpha^t (d\tau)^{-\alpha}, \mathrm{Re}(\alpha) > 0 \qquad (15)$$

where a & t are upper and lower bounds of integration, α is the order of operation. If α >0, then ${}_aD_t^{-\alpha}$ refers to fractional order integral and ${}_aD_t^{\alpha}$ refers to fractional order derivative [6]-[7]. The commonly used Grunwald-Letnikov definition given by,

$${}_aD_t^{\alpha} f(t) = \lim_{h \to 0} h^{-\alpha} \sum_{r=0}^{n} (-1)^r \binom{\alpha}{j} f(t - rh) \qquad (16)$$

$$\binom{\alpha}{0} = 1, \quad \binom{\alpha}{r} = \frac{\alpha(\alpha-1)....(\alpha - r + 1)}{r!} \qquad (17)$$

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The fractional order PI controller is based on the same principle as that of classical PI controllers, the only difference being the order of integration will be a non-integer [6]-[8]. The transfer function of a FOPI controller is given by,

$$C(s) = K_p + \frac{K_i}{s^{\alpha}} \qquad (18)$$

Where α indicates the order of integration, K_p& K_i are proportional and integral gains. In this work, the order of integration selected was 0.6.

VI. SIMULATION RESULTS

The proposed PMSM drive system is compared with an ordinary PMSM vector controlled system (sensored) and the results are obtained. Simulation model of the proposed system was developed with the help of MATLAB/SIMULINK interface. All the above mentioned techniques were developed according to the requirement and were interconnected to obtain the overall system. The proposed drive's model is shown below,

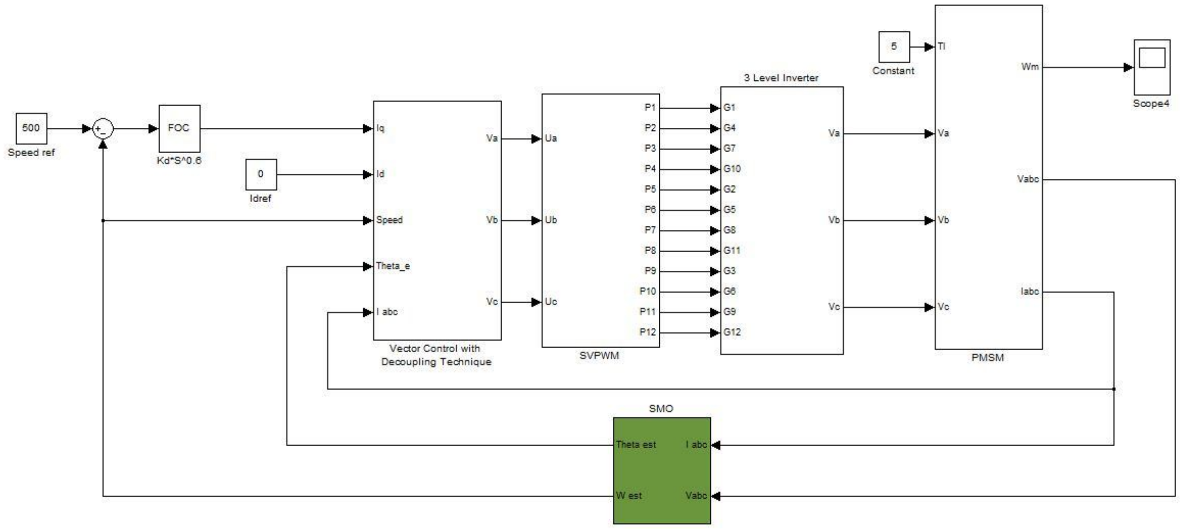

Fig. 3 Overall Simulation Diagram

A. Three Level Inverter Performance

The performance of the neutral clamped 3 level inverter was obtained as follows: The voltage of A phase is shown below:

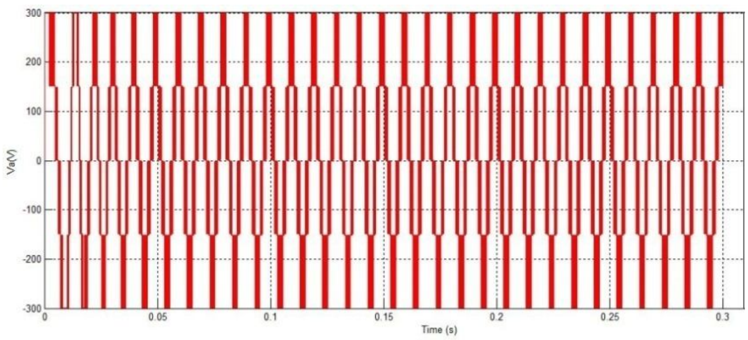

Fig. 4 Inverter Output Voltage.

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B. Torque Speed Characteristics

In this section, the torque speed characteristics are analysed. For a load torque of 10 Nm, Fig. No: 5 show the torque speed characteristics of the proposed system and Fig. No: 6 show the same as that of an ordinary vector controlled system [1]. From the figures 5 & 6, we can say that more smooth response can be obtained with the help of the proposed drive system. Also the starting torque of the proposed drive system is found to have improved in comparison

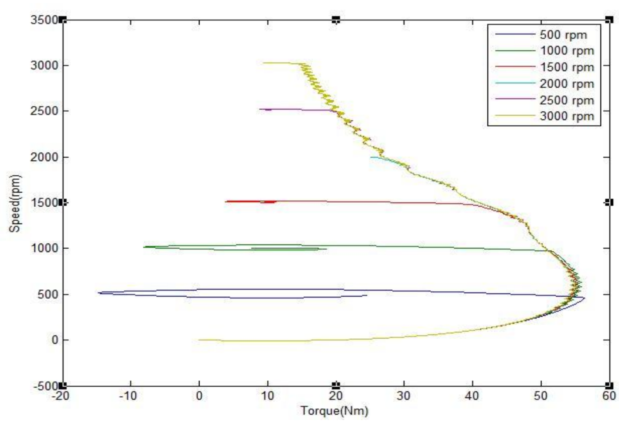

Fig. 5 T-N Characteristics of Proposed Drive.

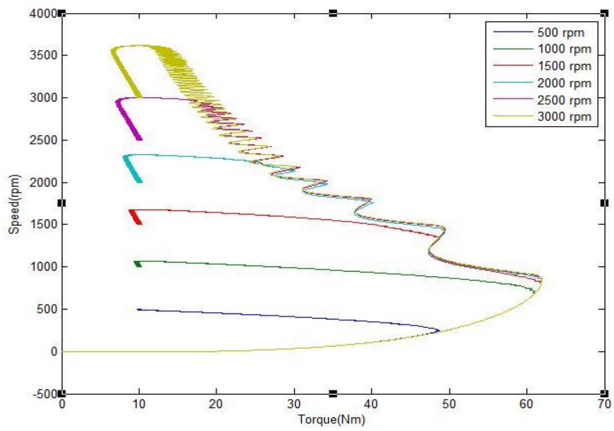

Fig. 6 T-N Characteristics of FOC of PMSM Drive.

C. Performance of the Proposed Sliding Mode Observer

A new and improved sliding mode observer was used in this technique, which gave the response as shown below. Both the estimated as well as actual position is shown in the figure. The next figure shows the estimation error. These two figures gives us the idea that the performance of the new sliding mode observer is satisfactory and can give the speed and position estimate with least error as possible. The position output wave form has negligible deformation, so we can say that the effect of chattering phenomenon is very less. The speed estimate is also compared with the actual speed which substantiates the usage of the improved sliding mode observer.

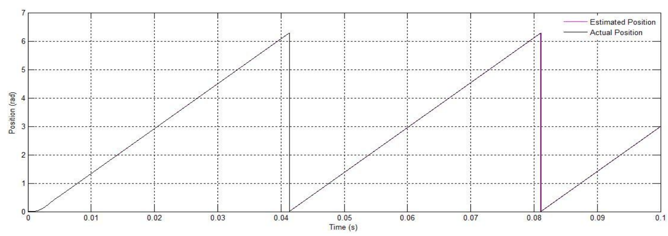

Fig. 7 Estimated & Actual Positions

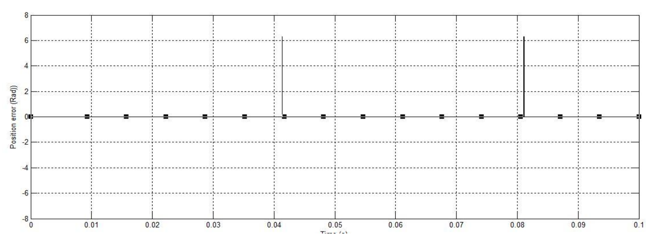

Fig.8 Position Estimation Error

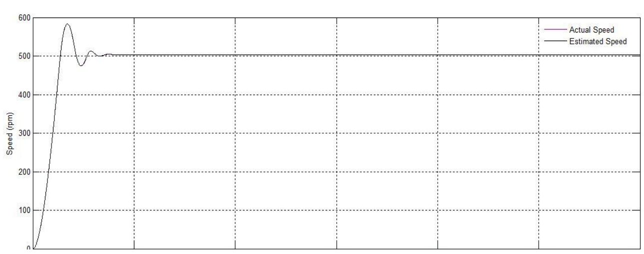

Fig. 9 Speed Estimation Performance of SMO

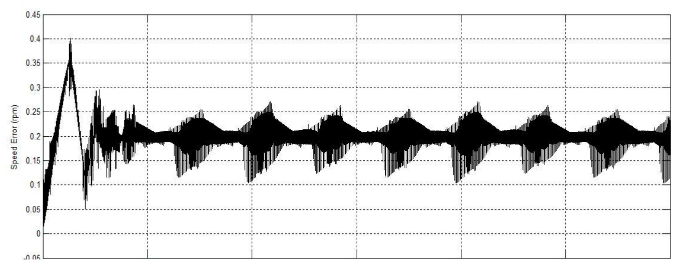

Fig. 10 Speed Estimation Performance of SMO

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D. Performance of FOPI Controller in Comparison with Classical PI Controller

The performance of FOPI and classical PI controllers are shown in Fig. No: 4. From the figure, it can be seen that for a reference speed of 1500 RPM, the response of FOPI controller was found to be far superior to the classical PI controller. The overshoot as well as settling time of the system was improved.

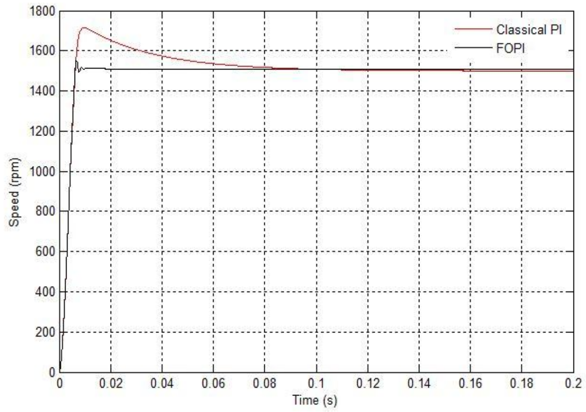

Fig. 11 Speed Response Comparison between Classical PI & FOPI

E. Torque Response

The torque responses for the ordinary vector control system for a load torque of 5Nm & the torque response for the proposed drive system under same conditions are shown below. These graphs indicate that the torque ripple reduction is significant with the help of the proposed system. The graphs are shown below

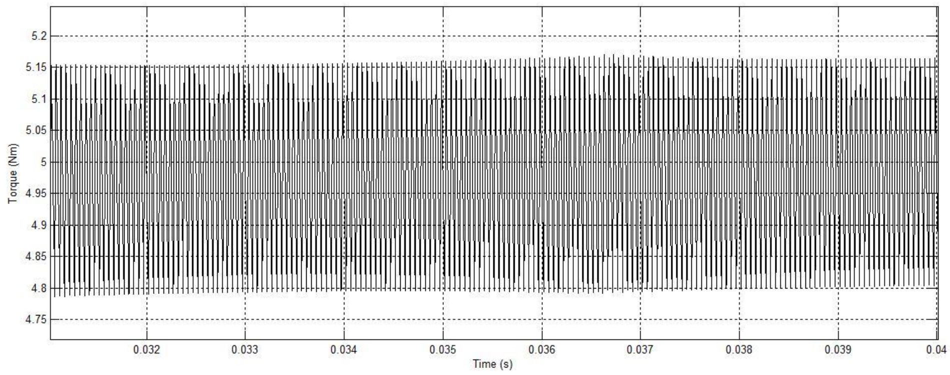

Fig. 12 Torque response of Vector Control of PMSM Drive

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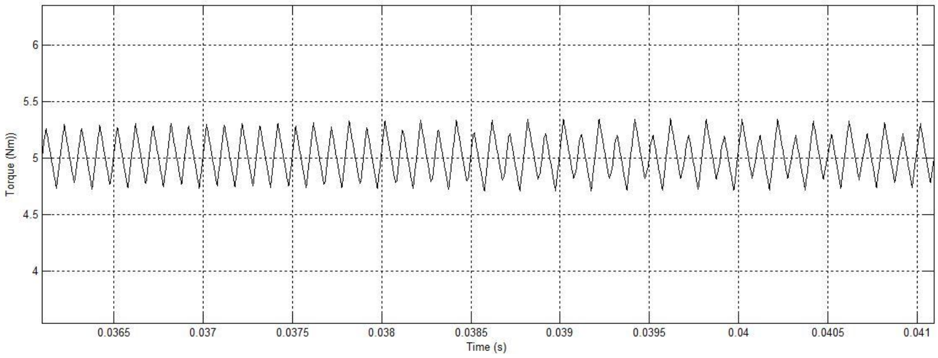

Fig. 13 Torque Response of Proposed PMSM Drive

VII. EXPERIMENTAL RESULTS

The experimental setup is as shown below. The experiment was done with TMS320F28035 DSP control card, a two level inverter, Anaheim made PMSM servo motor.

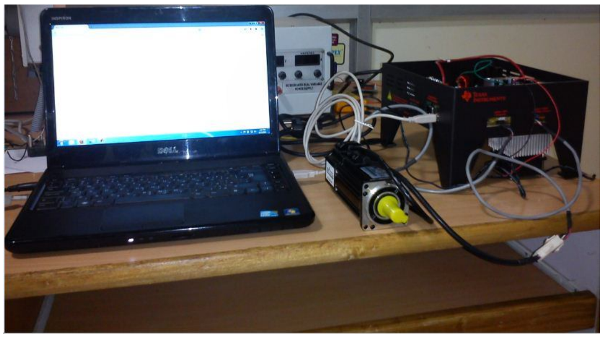

Fig. 14 Experimental Setup

Rated power (W)	Rated Speed (RPM)	Rated Torque (Nm)	Rated Current (A)	Resistance (Ohm)	Inductance (H)
400	3000	1.27	2.7	2.35	0.0065

Table 1 Motor Parameters

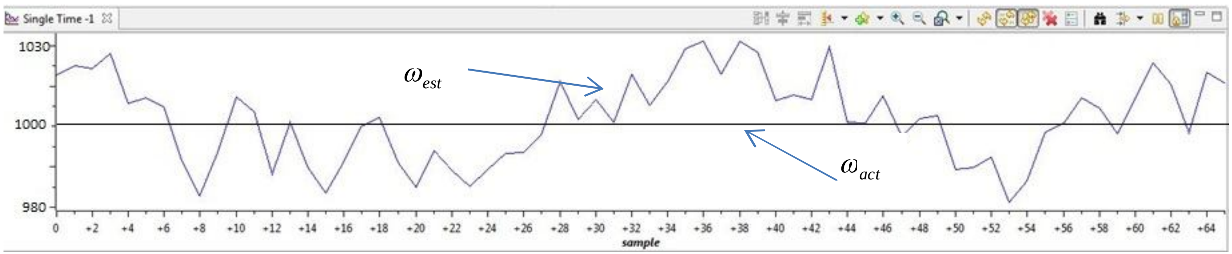

Fig. 15 Estimated and Actual Speed

The experiment was done with the help of DSP. The DSP employed was TMS320F28035 control card. PMSM used is of Anaheim made. The parameters of the motor are shown in Table 1. The experimental results are shown in Fig. 11 &12.

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From the graphs it can be said that the position and speed were estimated correctly and the closed loop operation of the drive was made possible in the hardware also.The motor was found to operate with less noise and the tracking performance was also satisfactory.

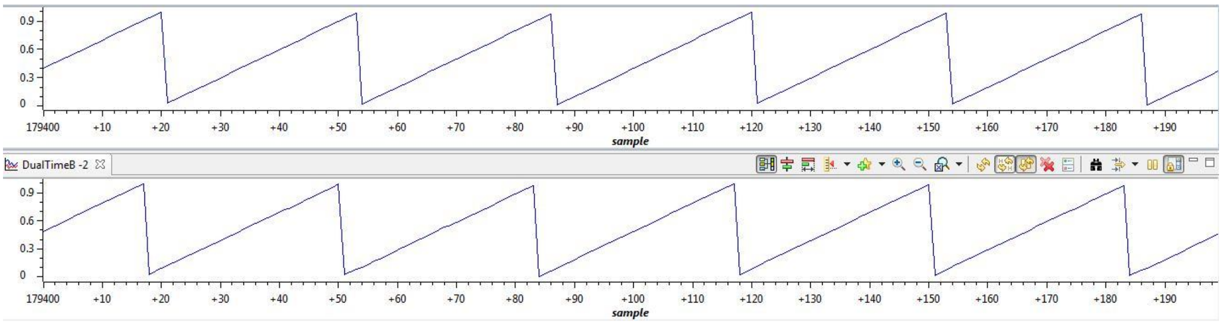

Fig. 16 Estimated (top) and actual (bottom) Positions of rotor

VIII. CONCLUSION

In this paper, a sensored vector control of PMSM was considered andvector control incorporating decoupling control technique was implemented. A new sensorless technique based on an improved sliding mode technique was introduced whose working was found to be more than satisfactory in simulation as well as in its hardware counterpart.With the help of SMO technique, position and speed were sensed with negligible error. Then a neutral point clamped three level inverter was used instead of a two level inverter which helped to reduce the heating of the winding due to harmonics and considerably reduced the stresses on the switches used. After these modifications, the torque response was found to have less torque ripples. Then the classical PI controller was replaced with a fractional order controller, which improved the performance of the system to a great level as shown in the results. So the proposed technique incorporating new sliding mode observer, three level inverter and fractional order PI controller into the ordinary vector control system for a PMSM drive was found to have more advantages than the basic system. Compared with the ordinary PMSM drives, the proposed technique can be said to have superior characteristics.

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