Comparative Performance of PMSM Drive using FOPI and PI Controllers under Dynamic Loads

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Abstract— The main objective of this paper is to design a permanent magnet synchronous motor (PMSM) drive for controlling speed under various operational conditions of loads. Modelling and simulation of the drive system was carried out using integer order (IO) PI and compared with the fractional order proportional integral (FOPI). Fractional order is applied in the IOPI controller and analysis was done for different dynamics. The use FOPI improves the performance of the PMSM drive system which is observed in output waveforms. The performance and robustness of the proposed controller were also tested.

Key words: PMSM, IOPI, FOPI, FOC

I. INTRODUCTION

In high performance applications, the Permanent Magnet Synchronous Motors (PMSMs) are becoming popular as compared to other types of ac motor due to some of their advantageous features including high torque, high power, high efficiency and low noise. Permanent Magnet Synchronous Motor (PMSM) has been widely used in high performance applications due to its advantages such as compactness, high efficiency, and reliability, high torque to current ratio and large power to weight ratio [1]. PMSM drive performance mainly depends on the quick and precise response of the system, as well as on the robustness of the control strategy [2]. In order to achieve dynamic performance, the vector control, also known as field-oriented control (FOC), of the PMSM drive is employed [3]. In fact, FOC relies on the space vector pulse width modulation (SVPWM) control strategy. By using SVPWM, the PMSM control becomes almost the same as the DC motor control [4].

In the FOC PMSM drive, the d-q axis current control plays an important role in determining the overall system performance [5]. Therefore, an intelligent current controller claims meticulous consideration for the high performance FOC PMSM drive systems. Moreover, the current controllers should be designed first to ensure current regulation with adequate dynamics and zero steady-state error, irrespective of the reference signals behind them [6]. There exist several controllers for controlling currents in FOC PMSM drives [7–8]. In order to eliminate the steady-state error, the proportional-integral (PI) controller can also be used. The controller design for PMSM model plays an important role in the system performance. Usually, the PI control is used in the speed loop of PMSM closed loop control system. Control algorithm of the conventional PI control strategy is easy to realize, so higher steady-state accuracy could be acquired and it could be widely used in engineering practice [9]. On the other hand, the adverse nonlinear nature of PMSM interior variables, the coupling characteristics and the external disturbances make it difficult to build the accurate mathematical model of controlled object and the controlled object often changes with the working condition. The expected control performance index could only be acquired through precise mathematical model and dynamic response of the system [10].The main advantage of conventional PI controllers is that they are easy to implement. However, conventional PI controllers suffer from problems due to changes in system dynamics or variation in operating points as a result of parameter variations. These problems may affect the system performance using controllers that have fixed parameters. To overcome such deficiency, more efficient controllers such as fractional order PI controllers are used by tuning the parameters on-line of the FOPI controller. [11]For the better understanding of fractional calculus a considerable amount of attention is given to the fractional-order controllers. Fractional order controllers are studied through modelling and control systems [12]. Due to the intensive research for developing both fractional PI and PID controllers. The performance of PI controllers with fractional order system can be improved by extending from integral order to fractional order.

II. PMSM DRIVES AND MODELLING

PM motor drives have been a research of interest for the last two decades. Many researchers have carried out mathematical modelling and simulation of PMSM drives. The permanent magnet (PM) synchronous motor possesses special features for adjustable speed operation. These machines are capable of operating at high motor and inverter efficiencies over wide speed ranges. The magnet cost was minimized by the low magnet weight requirements of the PM design. The electrical excitation requirements for the PM synchronous motor were also designed. PM motor drives are classified into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives. The application of vector control as well as complete modelling, simulation, and analysis of the drive system also aims to improve efficiency in permanent magnet (PM) synchronous motor drives. The modelling of PM motor was derived from the model of salient pole synchronous motor. All the equations were derived in rotor reference frame and were compared with the synchronously rotating reference frame.

A. The Mathematical Model of PMSM

The PMSM equations were developed in rotating reference frames. 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 the rotor are made negligible. In addition, there is no difference between the back EMF produced by permanent magnet and that produced by an excited coil. Hence the mathematical model of PMSM is similar to that of the wound rotor Synchronous Motor. The model of the PMSM is developed by using the following assumptions:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy current and hysteresis losses are negligible.
4) There are no field current dynamics.

With above assumptions, the stator d, q equations of the PMSM in the rotor reference frame are;

$$V_q = R_s i_q + L_p p i_q + \omega_r L_d i_d + \omega_r \phi_f \quad (1)$$

$$V_d = R_s i_d + L_d p i_d - \omega_r L_d i_q \quad (2)$$

Also flux can be written as;

$$\phi_d = L_d i_d + \phi_f \quad (3)$$

$$\phi_q = L_q i_q \quad (4)$$

Where V_q, V_d are the d, q axis voltages, i_d, i_q are the d, q axis stator currents, L_d, and L_q are the d, q axis inductances, ϕ_d and ϕ_q are the d, q axis stator flux linkages, Rs is the stator winding resistance per phase and ω_r is rotor electrical speed.

The electro mechanical torque is given by;

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)[\phi_f i_q - (L_d - L_q) i_q i_d] \quad (5)$$

And the equation of motor dynamics is;

$$T_e = T_L + B\omega_r + Jp\omega_m \quad (6)$$

Where P = number of poles,
T_L = load torque,
B = damping co-efficient,
ω_m = rotor mechanical speed,
J = moment of inertia and
p = differential operator.

$$\omega_r = \left(\frac{P}{2}\right)\omega_m \quad (7)$$

The PMSM is rearranged in first order differential equations form as,

$$p i_d = (V_d - R_s i_d + \omega_r L_q i_q)/L_d \quad (8)$$

$$p i_q = (V_q - R_s i_q - \omega_r L_d i_d - \omega_r \phi_f)/L_q \quad (9)$$

$$p\omega_m = (T_e - T_L - B\omega_m)/J \quad (10)$$

$$p\theta_m = \omega_m \quad (11)$$

$$\theta_m = \int \omega_m \quad (12)$$

Where θ_m = the rotor position angle,

In order to achieve maximum torque per ampere and maximum efficiency with linear characteristics, direct axis current component i_d and the reluctance torque is forced to zero.

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\phi_f i_q \quad (13)$$

The d, q variables are obtained from a, b, c variables through the park transform as;

$$V_q = 2/3[V_a\cos\theta + V_b\cos\left(\theta - \frac{2\pi}{3}\right) + V_c\cos(\theta + \frac{2\pi}{3}) \quad (14)$$

$$V_d = 2/3[V_a\sin\theta + V_b\sin\left(\theta - \frac{2\pi}{3}\right) + V_c\sin(\theta + \frac{2\pi}{3}) \quad (15)$$

The a, b, c variables are obtained from the d, q variables through the inverse of the park transform as,

$$V_a = V_q\cos\theta + V_d\sin\theta \quad (16)$$

$$V_b = V_q\cos\left(\theta - \frac{2\pi}{3}\right) + V_d\sin\left(\theta - \frac{2\pi}{3}\right) \quad (17)$$

$$V_c = V_q\cos\left(\theta + \frac{2\pi}{3}\right) + V_d\sin\left(\theta + \frac{2\pi}{3}\right) \quad (18)$$

The torque equation is similar to that of separately excited dc motor, and this completes the transformation of a PMSM to an equivalent separately excited dc motor.

III. PROPOSED SYSTEM

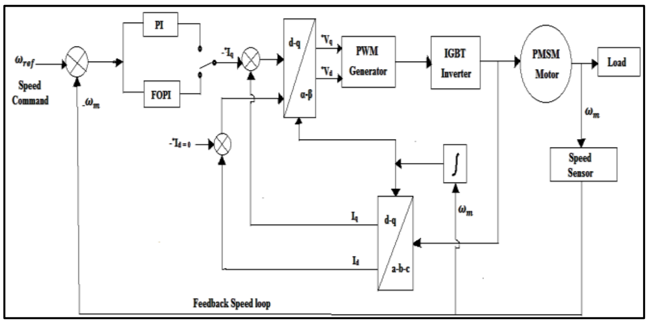


Fig. 1: Block diagram of proposed model

The basic idea of vector control implementation is explained with the help of fig 1, where the machine model is represented in a synchronously rotating frame of reference. The IGBT inverter is used for better switching and generates currents i_a, i_b and i_c as dictated by the corresponding common currents i_a*,i_b* and i_c* from the controller. The machine terminal phase currents i_a i_b and i_c are converted to i_d and i_q components by 3phase/2phase transformation. These are then converted to synchronously rotating frame by the unit vector component $cos\theta$ and $sin\theta$ before applying them to the d- q machine as shown. The controller makes two stages of inverse transformation, as shown, so that the control currents i_d* and i_q* corresponds to the machine currents ids and i_q, respectively. In addition, the unit vector assures correct alignment of i_d current with the flux vector and i_q perpendicular to it, as shown. Note that the transformation and the inverse transformation including the inverter ideally do not incorporate any dynamics, and therefore, the response to ids and i_q is instantaneous. Then the stimulation was carried out for both the controller using PI and FOPI controllers under various operating conditions of loads.

IV. CONTROLLER DESIGN

A. PI Controller

The PI controller is a controller where P stands for proportional control and I for integral control. The basic function of a controller is to execute an algorithm based on the control engineer's input (tuning constants), the operator's desired operating value (set point) and the current plant process value [14-15]. In most cases, the requirement is for the controller to act so that the process value is as close to the set point as possible. In a basic process control loop, the control engineer utilizes the PI algorithms to achieve this. A PI controller is used for both transient and steady-state responses, proportional-integral (PI) control offers the simplest and most efficient solution to many real-world control problems. The PI controllers are usually standard building blocks for industrial automation. The most basic PI controller has the form:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)d(t) \quad (19)$$

Where u(t) is the control output

e(t) is the error signal = desired value – measured value of quantity being controlled

K_p and K_i are the controller gains

Therefore, PI controller in frequency domain can be written as:

$$C(s) = \frac{u(s)}{e(s)} = K_p + \frac{k_i}{s} \quad (20)$$

Where K_p is the proportional gain coefficient and K_i is the integrator coefficient. The proportional gain is used to amplify the input signal. The integrator is used to improve the accuracy of the control system, that is, to minimize the steady-state error as much as possible.

B. FOPI Controller

The FOPI controller is an extension of the Integer Order (IO) PI controller with an additional term α. This term is being added to the controller's integral part [16].

The FOPI controller in the frequency domain is simply written as:

$$C(s) = \frac{u(s)}{e(s)} = K_p + \frac{K_i}{s^{\alpha}} \qquad (21)$$

Where α are an arbitrary real numbers, K_p and K_i are the proportional gain and integral gains of the fractional controller and α is the fraction value of PI controller.

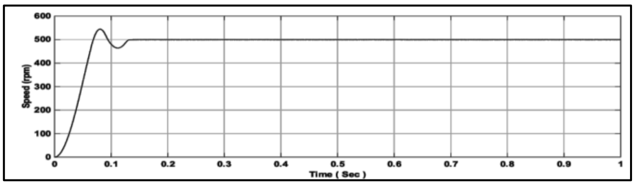
The FOPI controller is more flexible and has a better opportunity to adjust the dynamics of control system. It's compact and simple but the analog realization of fractional order system is very difficult. Intuitively, the FOPI has more degree of freedom than the conventional PI. It can be expected that the FOPI can provide better performance with proper choice of controller parameters.

V. RESULT ANALYSIS

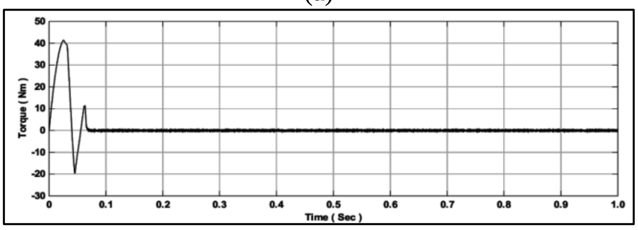
In this comparative study, the performance of PMSM drive for PI and FOPI controllers were carried out in MATLAB/ SIMULINK 2014b environment under different loading conditions and results were compared for better output under same load conditions. The parameters such as speed and torque variations were study for both controllers under bellow cases.

A. Case 1

In this condition, the motor drive is run at no-load with a speed of 500 rpm for time duration of 1 sec and following waveforms were stimulated for both FOPI and PI controllers.

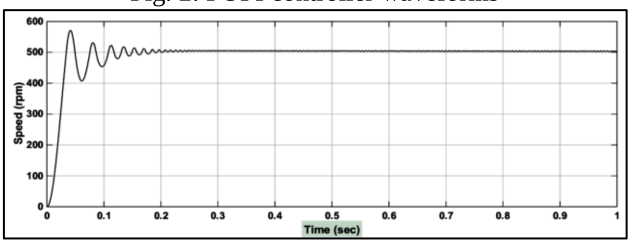


(a)



(b)

Fig. 2: FOPI controller waveforms



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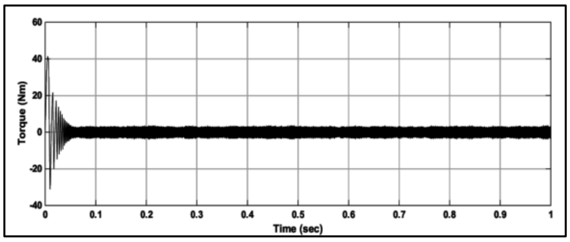


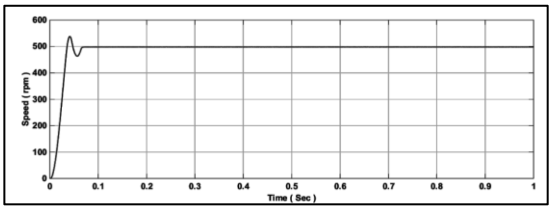
(b)

Fig. 3: PI controller waveforms

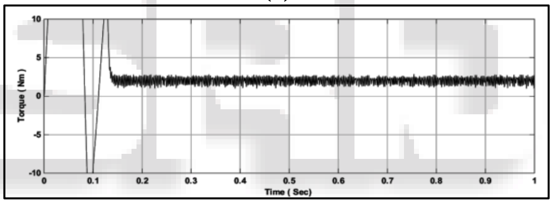
From above waveforms of fig. 2 (a) & 3 (a), it is concluded that the speed of PMSM drive using FOPI controller has less settling point than PI which is before 0.2 sec and has very less overshoots and undershoots for attaining steady state. Whereas fig. 2 (b) & 3 (b) shows that electromagnetic torque pulsation is more in PI controller than FOPI for its normal operation.

B. Case 2

In this case the motor is operated for a mechanical load of 2 Nm at 500 rpm speed for 1 sec and following observations in waveform were stimulated as follows:

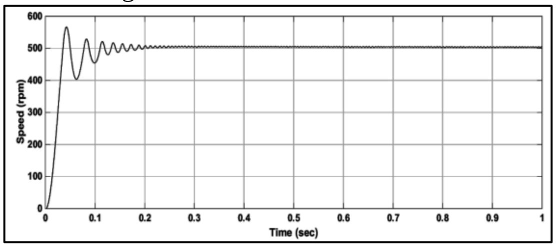


(a)

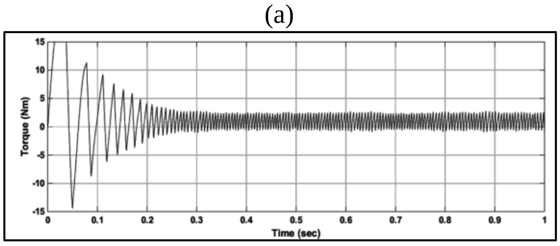


(b)

Fig. 4: FOPI controller waveforms



(a)



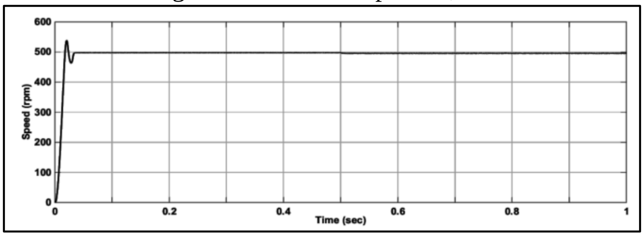
(b)

Fig. 5: PI controller waveforms

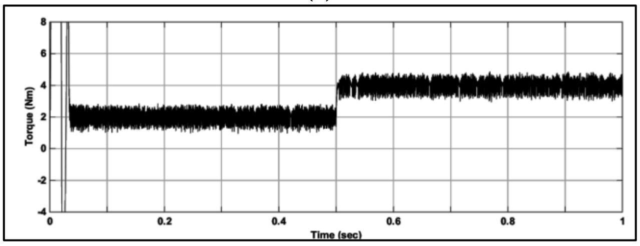
Here the waveforms for speed in fig. 4 (a) & 5 (a) for constant load shows no variation when the motor is loaded, the FOPI controller executes better than traditional PI controller and steady state is obtained before 0.1 sec than PI with less overshoots and undershoots. Fig. 4 & 5 (b), shows electromagnetic torque using PI has more disturbance than FOPI controller.

C. Case 3

The speed of the motor is a step signal with magnitude of 500 rpm. The dynamic load from 2 Nm to 4 Nm was introduced in motor for a period of 1sec dynamics were occurred at 0.5 sec and following waveforms were plotted;

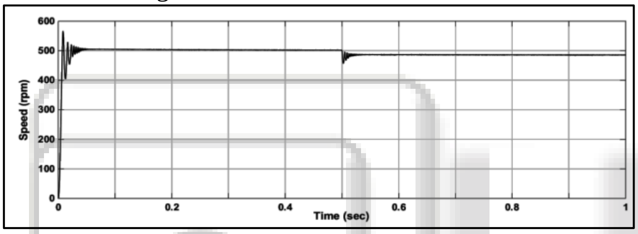


(a)

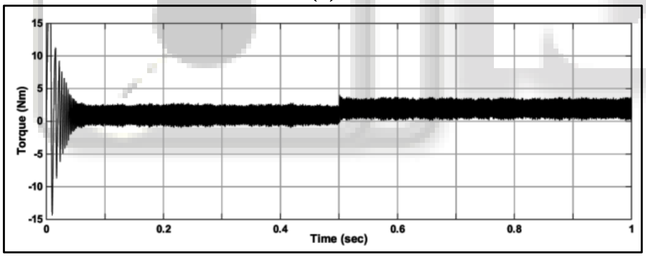


(b)

Fig. 6: FOPI controller waveforms



(a)



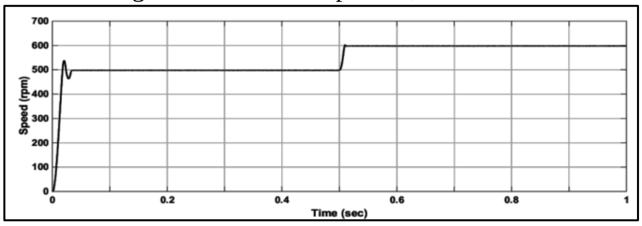
(b)

Fig. 7: PI controller waveforms

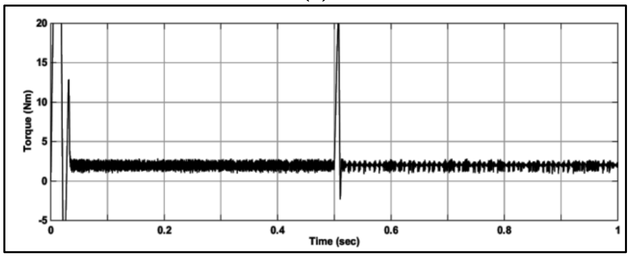
From waveforms 6 & 7 (a), it is observed that when load dynamics takes there is a slight dip in speed (i.e. 12 rpm) with no disturbance by FOPI controller but whereas some overshoots occurs with more speed variation by PI controller which can seen at 0.5 sec of the stimulation period. The electromagnetic torque is smooth in FOPI rather than PI controller while change in load during dynamics.

D. Case 4

The initial speed of the motor was a step signal of magnitude 500 rpm and then dynamically changed to 600rpm at 1sec for a load of 2 Nm which was stimulated for a period of 2sec and following waveforms were plotted;

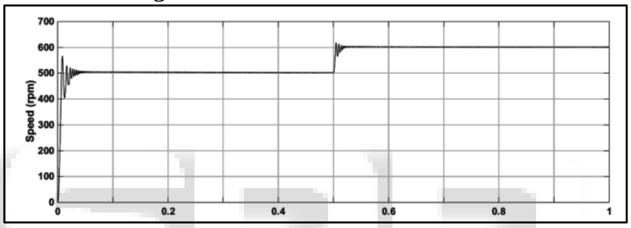


(a)

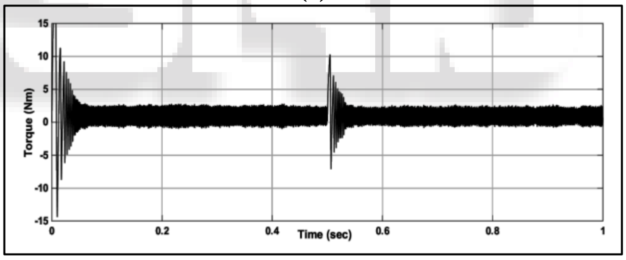


(b)

Fig. 8: FOPI controller waveforms



(a)



(b)

Fig. 9: PI controller waveforms

When speed change occurs at 0.5 sec instant of the stimulation period of 1 sec, the FOPI controller offers smooth control whereas PI does not allow proper dynamics for steady state operation which is seen in fig. 8 & 9 (a). The electromagnetic torque pulsation band width in FOPI is more in compare to PI controller and distortion during speed change is also more than FOPI.

Conditions	Observations from Stimulated Waveforms	
	FOPI Controller	PI Controller
No-Load	Overshoots in speed settles before 0.2 sec of its operation. Torque pulsation bandwidth is -0.5 Nm to 0.5Nm.	Overshoots in speed settles after 0.2 sec of its operation. Torque pulsation bandwidth is -3 Nm to 3Nm.
Constant Load	At 2 Nm load Overshoots settles at 0.1 sec of its operation. Torque pulsation bandwidth is 0.5 Nm to 2.5 Nm.	At 2 Nm load Overshoots settles at 0.2 sec of its operation. Torque pulsation bandwidth is -0.5 Nm to 3.5 Nm.
Dynamic Load	During dynamic load the dip in speed is observed as 4 rpm.	During dynamic load the dip in speed is observed as 12 rpm.
Dynamic Speed	When speed change takes place there is no overshoot in waveforms.	When speed change takes place there is slight overshoots in waveforms.

Table 1: Observations from Stimulated Waveforms

VI. Conclusion

In this paper presented comparative study between PI and FOPI controller that was carried out under different loading conditions and the results were stimulated and compared. The results show that the PMSM drive with FOPI controller shows better output response compared to traditional PI controller in all aspects. The study focuses in reduction of complexity in designing controller for PMSM drives. It is found that FOPI result is better in accord to conventional PI drive introduced in it.

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