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The control of permanent magnet synchronous motor drive based on the space vector pulse width modulation and fractional order PID controller

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ABSTRACT

This study explains a new way to speed control for PMSMs based on the FOC and SVPWM techniques employed in the building of the permanent magnet synchronous motors (PMSMs). When it comes to current control, two inner and one outside feedback loops were used. Feedback control with FOPID controllers is used to optimize the performance of PMSM motor design. FOPID parameters were optimized using genetic algorithms in MATLAB/Simulink simulations. Good dynamic and static qualities are demonstrated through simulation results. There is also a comparison of PMSM PID and FOPID controllers included.

Keywords: PMSM, VSI, SVPWM, FOC, Speed control, FOPID

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1. Introduction

Because of their efficiency, power density, torque-to-inertia ratio, and dependability, permanent magnet synchronous motors (PMSMs) have recently grown in popularity among ac drives. This is in part owing to ongoing reductions in the price of magnetic materials and in part to the advantages of PMSMs (e.g. neodymium-boron iron and samarium cobalt). Industrial applications that have made use of PMSM include devices like robots and CNC machines as well as electric cars. A number of prior studies have presented a space vector pulse width modulation (SVPWM) algorithm with a field-oriented control (FOC) technique, applied to PMSM drives, and many researchers employed PI controllers for speed and current control [1-9]. Although the PID controller is commonly used in practical applications, but in the last decade, fractional calculus has been applied in an increasing number of fields, namely in the area of control theory [10-16]. To achieve the optimization in this research work, the model of PMSM has been built in MATLAB/ Simulink, the SVPWM technique simulated using Fractional Order (**$PI^{\lambda}D^{\mu}$**) (FOPID) controller for speed and current control. A comparison is drawn between the performance of PID and FOPID controller based on their results.

2. Mathematical modeling of PMSM

With 3-phase stator and rotor windings, the PMSM contains permanent magnets. Pole pairs are separated by $2\pi/3$ electrical radians, and the stator windings are spread among them. Following are the PMSM equations represented in rotor reference frame [17, 18]:

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \omega_r i_q + \frac{1}{L_d} v_d \tag{1}$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{L_d}{L_q} \omega_r i_d - \frac{1}{L_q} \omega_r \psi_f + \frac{1}{L_q} v_q \tag{2}$$

$$T_{em} = \frac{3}{2}\frac{p}{2}(\psi_d i_q - \psi_q i_d) \tag{3}$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_{em} + T_{mech} + T_{damp}) \tag{4}$$

Where i_d, i_q, v_d, v_q stand for stator currents and voltages in d-.q axis, L_d, L_q are the dq rotor inductances, R_s is stator resistance , ω_r is rotor angular velocity,ψ_d, ψ_q stand for flux linkage when referring to d and q axis, ψ_f stands for s the permanent magnet flux, J stands for the rotor inertia ,T_{em} is electromagnetic torque,T_{damp} is fractional torque and T_L is load torque.

3. Three phase VSI with SVPWM method

The 3-phase Voltage source inverter (VSI) stands for a power converter used to provide three phase voltage-with controllable amplitude and frequency-to feed the stator winding for PMSM. The SVPWM stands for a control technique, used for controlling the output voltage and frequency of the inverter. According to SVPWM method, the three phase voltages converted into voltages in the stationary $\alpha - \beta$ reference frame, so that, a value of the reference voltage (Vref) is obtained. The hexagon shape in Fig.1 describes the result of two zero vectors ($V_0$and V_7) and 6 non-zero vectors (V_1 to V_6). The eight cases for switching the VSI are obtained in Table 1 [18].

Table 1. The Switching states of SVPWM

Voltage vectors	Switching State			phase voltage			Line voltage		
	A	B	C	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
v_0	0	0	0	0	0	0	0	0	0
v_1	1	0	0	$2/3$	$-1/3$	$-1/3$	1	0	-1
v_2	1	1	0	$1/3$	$1/3$	$-2/3$	0	1	-1
v_3	0	1	0	$-1/3$	$2/3$	$-1/3$	-1	1	0
v_4	0	1	1	$-2/3$	$1/3$	$1/3$	-1	0	1
v_5	0	0	1	$-1/3$	$-1/3$	$2/3$	0	-1	1
v_6	1	0	1	$1/3$	$-2/3$	$1/3$	1	-1	0
v_7	1	1	1	0	0	0	0	0	0

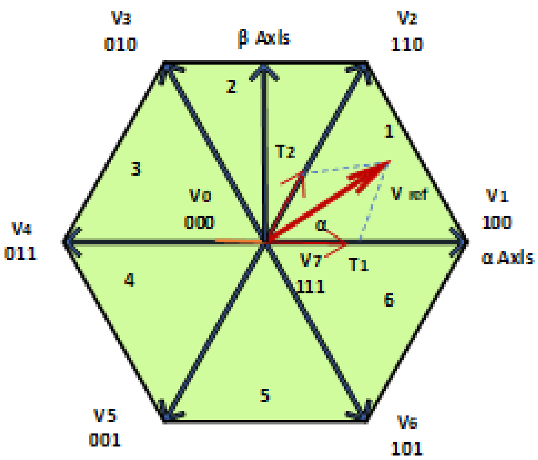

Figure 1. Voltage sectors of SVPWM

4. Field Oriented Control (FOC)

FOC theory can be used to change the three-phase currents and speed of the motor to remove the required vd and vq voltages from the stator current vector of PMSM. There are three-phase stator currents that can be converted to two-phase currents using the FOC theory. A speed sensor can be employed for measuring the vehicle's speed and compare it to a reference speed. Then, the FOPID controller may be utilized to produce a reference for quadrature current iq, which is used to modify the torque of the PMSM. In order to get the appropriate quadrature voltage vq, a second FOPID controller is utilized to compare the PMSM with the reference iq. Finally, a second FOPID controller has employed for comparing the direct axis current id with zero with the intention of acquiring the requisite voltage vd. For getting all-out torque control, iq and id had to be set to zero values. Figure 2 depicts the FOC procedure [19].

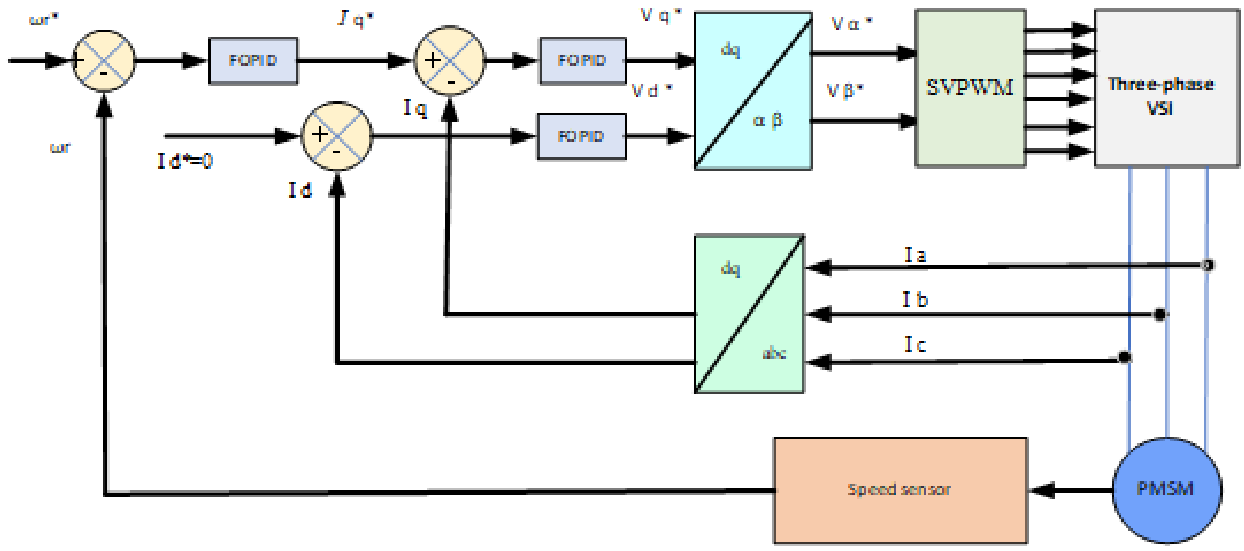

Figure 2. FOC strategy

5. Control design using FOPID controller

Fractional Order PID ($PI^{\lambda}D^{\mu}$) Controller is an expansion of a traditional PID controller, where integration and derivation order have fractional values. The modified controller with λ and μ orders for integral and derivative, make the system more flexible and less sensitive [20-26]. $PI^{\lambda}D^{\mu}$ controller can be characterized by the differential formula as:

$$u(t) = K_p\, e(t) + Ki\, D^{-\lambda} e(t) + K_d\, D^{\mu}\, e(t) \tag{5}$$

While the FOPID transfer function can be described by Laplace transform as follow:

$$G(s) = K_p + K_i\, S^{-\lambda} + K_d\, S^{\mu} \tag{6}$$

The conventional PID may be realized by taking λ =1, μ =1. Consequently, classical PI and PD controllers can produce if λ = 1, μ = 0 , λ = 0, μ = 1 and correspondingly.

6. Simulation and consequences

The whole PMSM model has been employed based on Simulink/MATLAB software version (2021a) as shown in Figure 3, with an optimal FOPID controller and SVPWM approach. In Table 2, the PMSM parameters are listed.

Table 2. PMSM parameters

variable	Physical meaning	value	Unit
P	Number of poles	4	Poles
La	Armature Inductance	5.25	mH
Rs	Armature Resistance	0.958	Ω
B_m	Damping Coefficient	$3035*10^{-7}$	N.m.sec
Ψ_s	Stator Flux Linkage	0.1827	V.sec
Jm	Moment of Inertia	$6329 *10^{-7}$	Kg .m^2

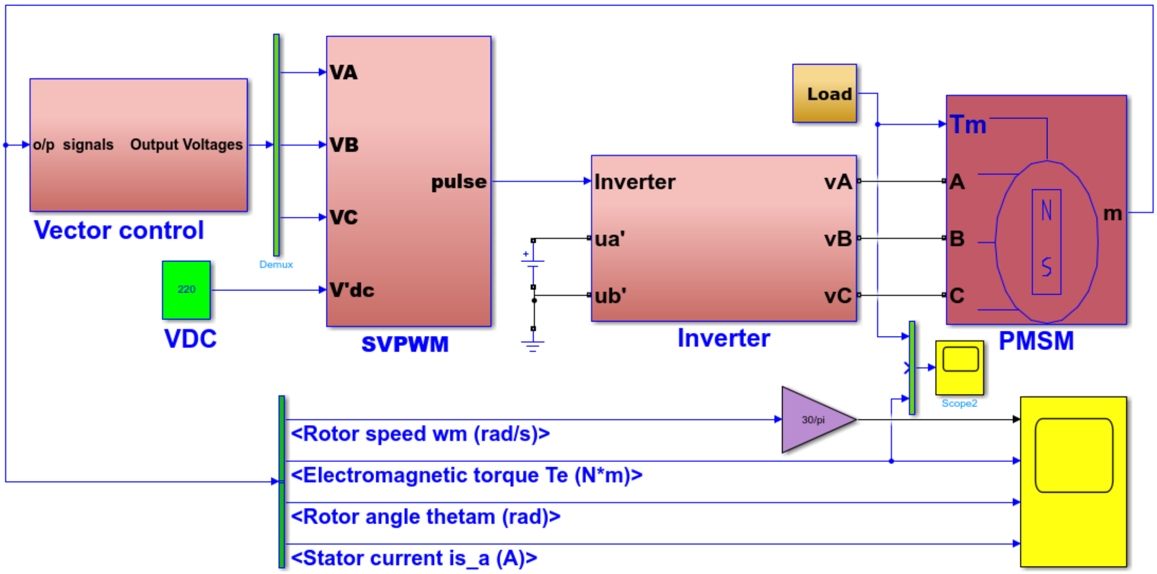

Figure 3. Simulink model of PMSM with FOC system structure diagram based on SVPWM

The FOPID controllers are Tuned by Genetic algorithm using "Check step response characteristics block "from the Simulink library, and the result of tuning specified in Table 3

Table 3. The optimal considerations of FOPID controller

Parameter	Value	Parameter	Value	Parameter	Value
K_{p1}	8	K_{p2}	4	K_{p3}	4
K_{i1}	34	K_{i2}	10	K_{i3}	10
K_{d1}	0.001	K_{d2}	0.001	K_{d3}	0.001
λ_1	1.9	λ_2	0.9	λ_3	0.9
μ_1	1.1	μ_2	0.9	μ_3	0.9

Figure 4 shows the speed responses of PMSM based on FOPID and PID controllers at the reference speed 800 (rpm). with dynamic torque change at t= 0.5 sec from 2 Nm to 4Nm.

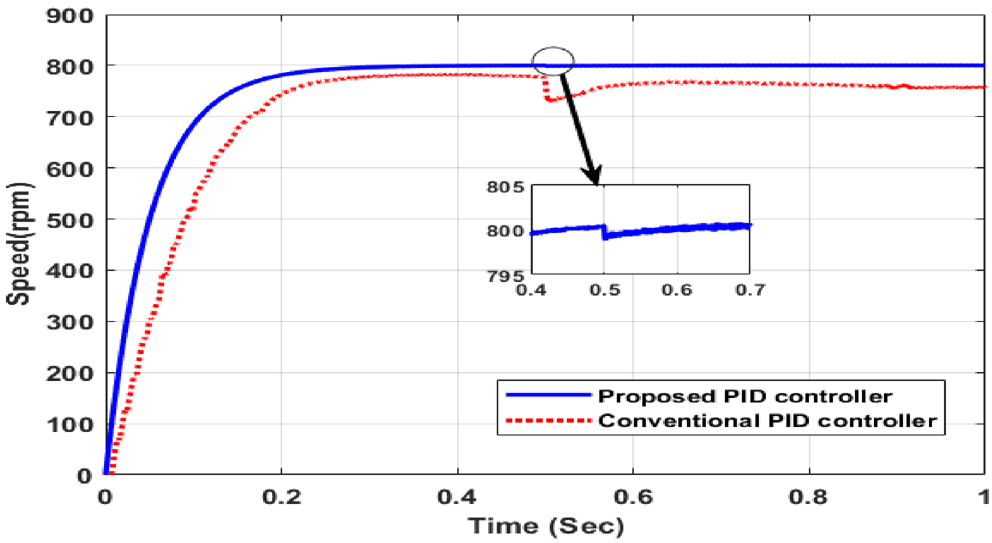

Figure 4. The speed responses of PMSM based on PID and FOPID controllers

The developed PMSM torque has depicted in Figure 5.

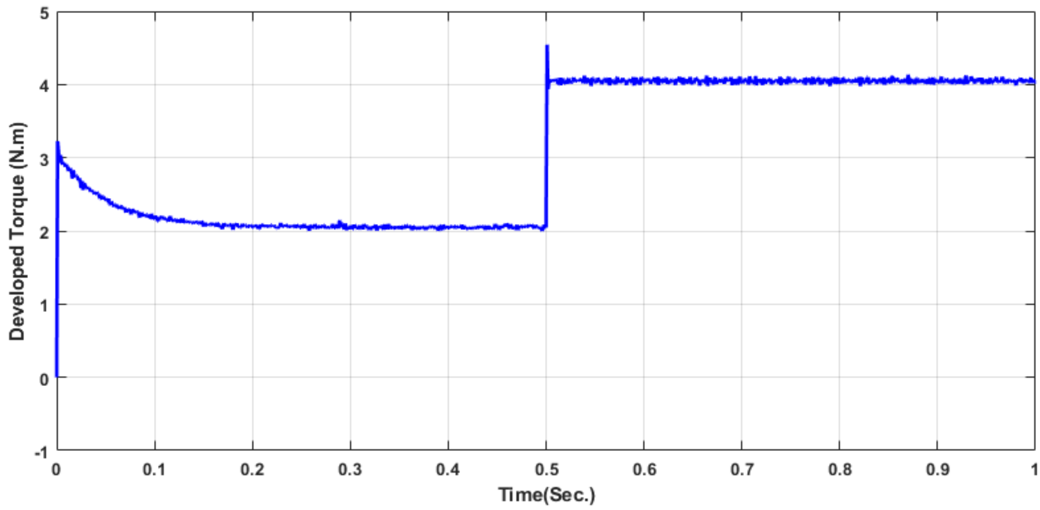

Figure 5. The developed torque of PMSM

While Figure 6 explains a current response of PMSM, and Figure 7 explains the phase A voltage.

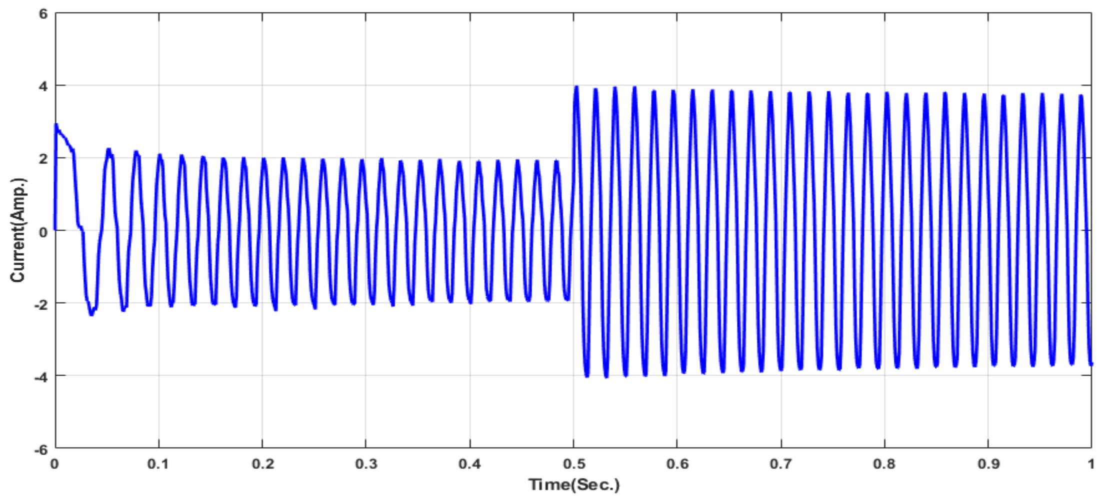

Figure 6. A current response of PMSM

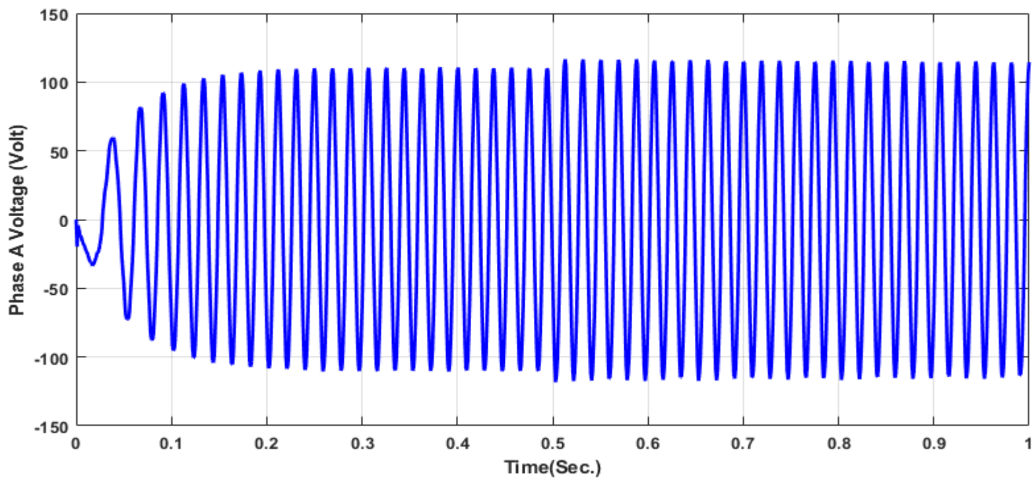

Figure 7. A phase A voltage of PMSM.

Furthermore, and to experiment the validity of FOPID controller on PMSM, numerous tests were done under diverse operating conditions, as shown in Figure 8.

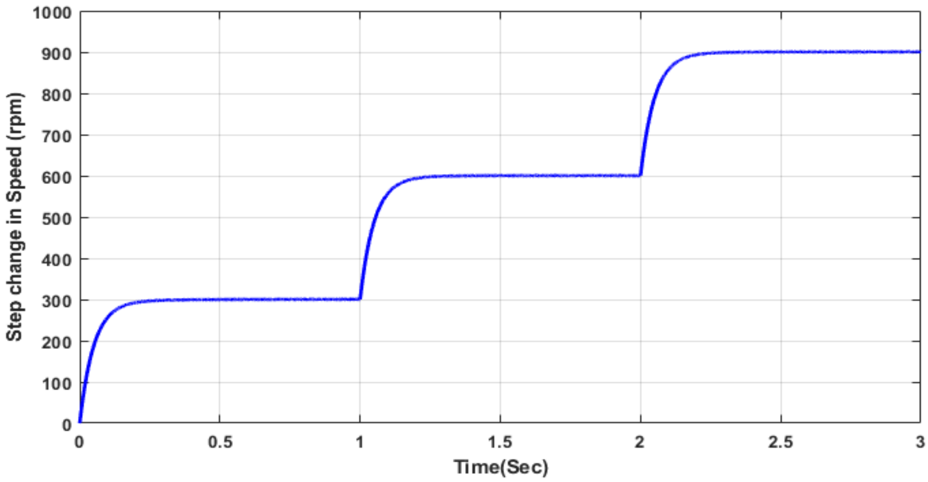

Figure 8. Speed output based on step change with respect to reference speed

The engine is started at 300 rpm, then increased to 600 rpm after one second, and lastly increased to 900 rpm after two seconds. A sudden increase in torque load of 2 N.m at time 1 Sec and a subsequent increase of 4 Nm occurs at time 2 Sec and at a reference speed of 300 rpm as a result of a step change in torque load.

7. Conclusions

MATLAB/Simulink was employed to simulate the SVPWM closed loop system with the suggested controller. Optimal FOPID controllers have greater performance than integer PID controllers in terms of smooth transitions over a wide range of dynamic load circumstances and faster response times, according to computer simulations. In addition, the suggested PID controller has a lower steady state error and no discernible overshoot.

Declaration of competing interest

No financial or non-financial conflicts of interest have been identified in this paper's content.

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