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Modeling and Time Response Analysis of a PMSM for Small Utility Electric Vehicles with P, PI and PID Controllers

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***Abstract*—Permanent magnet synchronous motors (PMSM) can be used directly in place of induction motors (I.M.) for several commercial and industrial applications since they are characterized by high efficiency, a high power factor, and a high power density compared to I.M. This paper presents the mathematical modeling of a vector-controlled Permanent Magnet Synchronous Motor (PMSM) drive. The performance analysis of the motor with proportional controller (P), proportional-integral controller (PI), and proportional-integral-derivative controller (PID) as a driving system has been studied and compared. A simulation study was conducted under diverse speed conditions, utilizing step changes as the basis. Subsequently, a comprehensive performance analysis was undertaken, involving the plotting of various parameters, including three-phase ABC currents, two-phase dq current, speed, and torque. [1]. The vector control system model includes PMSM, a SVPWM inverter, the speed controller, and vehicle dynamics for speed control. The performance analysis of the drive is evaluated for step changes under transient conditions for overshot, settling time, rise time, and steady state error of speed for specifically designated values validated by MATLAB/Simulink in all methods. In synchronous machines, the conventional electromagnetic field poles in the rotor are replaced by permanent magnets, and by doing so, the slip rings and brush assembly are eliminated, requiring less electric energy and a compact design. Due to the absence of field or rotor current, the efficiency of the motor is very high for commercial applications. [3]–[5]**

Keywords: Permanent Magnet Synchronous Motor (PMSM); electric vehicle dynamics; proportional (P) controller; proportional integral (PI) controller; proportional integral derivative (PID) controller; Space vector pulse width modulation (SVPWM)

***Index Terms*—Permanent Magnet Synchronous Motor (PMSM); Proportional (P) controller; proportional Integral (PI) controller; proportional Integral Derivative (PID) controller**

I. INTRODUCTION

Small electric utility applications frequently use permanent magnet synchronous motors. Compared to asynchronous machines, this kind of motor is widely used in industrial applications because of its durability, high power density, ease of control, and compact size. Vehicle carbon emissions have decreased in recent years due to a number of environmental factors. Alternatives to conventional automobiles with SI or CI engines are electric vehicles (EVs). [1]. A constant switching frequency is required for a vector-controlled PMSM drive, which offers reduced torque ripples and better dynamic responsiveness. Proportional-integral (PI) controllers are thought to be the most helpful tuning technique for d-q axis currents and speed control loops because of their adaptability and simplicity. The Proportional (P), Proportional-integral (PI) and Proportional-integral-Derivative (PID) controllers are compared for the time response analysis of the PMSM for the sudden acceleration. [2]

II. MATHEMATICAL MODEL OF THE PERMANENT MAGNET SYNCHRONOUS MOTOR

A mathematical design was made for a three-phase salient-pole PMSM im Matlab Simulink using the motor dynamic equations. Table I contains the model specifications. [6] The PMSM's mathematical model is provided in (1)–(9). Because the rotor magnet's location will be ascertained without regard to the machine's torque, immediate induced phase EMFs, stator phase currents, or stator phase voltages, the rotor reference frame was selected and the following assumptions are made:

-The saturation of the iron in the stator of the motor is ignored -The effects of the eddy current and hysteresis are ignored -The three-phase windings of the stator are symmetrical. The Permanent Magnet Synchronous Motor model can be described in the form of the following nonlinear mathematical

TABLE I

Parameter	Value
Stator phase resistance, Rs	2.98 Ω
d-axis inductance, Ld	7x10-3H
q-axis inductance, Lq	7x10-3H
Flux linkage,	0.125Wb-turn
Inertia, J	0.47x10-4 Kgm2
Viscous damping, B	11x10-5 Nm
Pole pairs, P	2

equations in the d-q reference frame.

$$\frac{di_d}{dt} = \frac{1}{L_d}(V_d + L_q\omega_e i_q - R_s i_d) \tag{1}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}(V_q - R_s i_q - L_d\omega_e i_d - \phi_m\omega_e) \tag{2}$$

Electromagnetic torque equation

$$T_e = \frac{p}{2}(\frac{3}{2})(\phi_d i_q - \phi_q i_d) \tag{3}$$

$$\phi_d = L_d i_d + \phi_m \tag{4}$$

$$\phi_q = L_q i_q \tag{5}$$

$$T_e = \frac{p}{2}(\frac{3}{2})(L_d - L_q)i_d i_q + \phi_m i_q \tag{6}$$

this is the equation for direct axis flux linkages. Eq (4) represents direct flux Mechanical torque

$$T_e = T_L + B\omega_m + J(\frac{d\omega_m}{dt}) \tag{7}$$

$$\omega_e = \frac{p}{2}(\frac{1}{Js + B})(T_e - T_L) \tag{8}$$

$$\theta_r = \int_0^t \omega_e(t)dt + \theta_r(0) \tag{9}$$

Park Clark transformation matrices are given by

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin\theta & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin\theta & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

III. FIELD ORIENTED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM)

Typically, the machine's flux value is adjusted by the stator axis component, which also serves as the excitation. The torque is controlled by the q axis component, which also serves as the armature current. The axis of the component i_q must be in quadrature with respect to the rotor flux in order to apply vector control. In the case of a surface-mounted PMSM, $L_d = L_q$. The direct current needs to be $i_d = 0$ when field-oriented control is applied and the system is operating at optimal linear torque. [4]–[6] This means that: $i_d = 0$, $i_q = i_s$, $\phi_d = \phi_f$

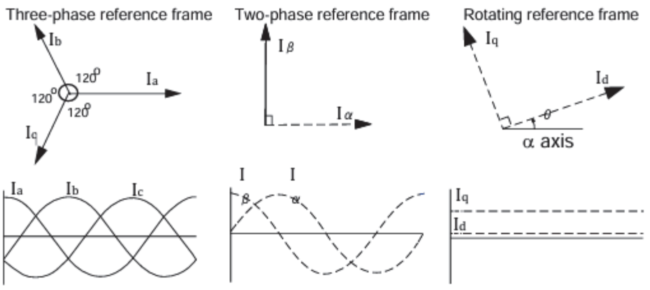

Fig. 1. Three phase rotating to two phase rotating vector transformation

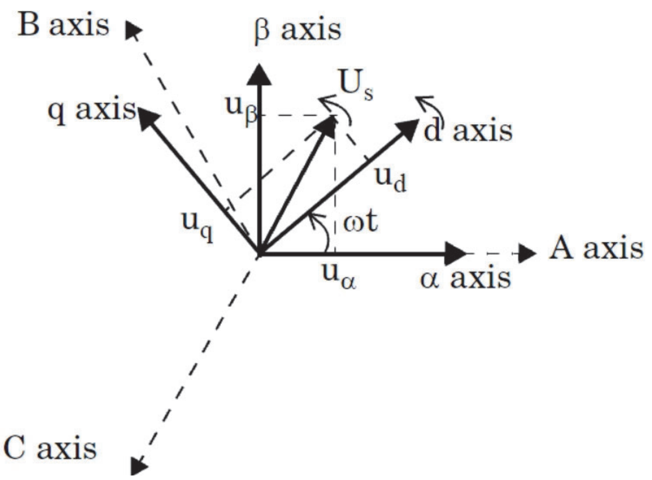

Fig. 2. Phase diagram of the PMSM in the frame of reference linked to the rotating field

The rotor position information is required for the FOC of the motor. This is provided by an encoder or resolver and speed is calculated from rotor position (θ). Motor speed is compared with reference speed and the error is fed as input to the controller whose output will be proportional to torque producing component of stator current (i_{qref}). This current is compared with q-axis component of stator current (i_q) and error is fed to another PI controller to find q-axis reference voltage component V_{qref}. The d-axis component of stator reference current which is the flux producing component (i_{dref}) is taken equal to zero to satisfy maximum torque per ampere condition. [5]–[7] This current is compared with motor d-axis current component and the error is fed to PI controller to find V_{dref}.

IV. PROPOSED SYSTEM MODEL WITH P, PI AND PID CONTROLLER

For applications in control theory, the Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) controllers are the most commonly used controllers. The PI controller will affect the performance of the system by increasing the system's order by one and

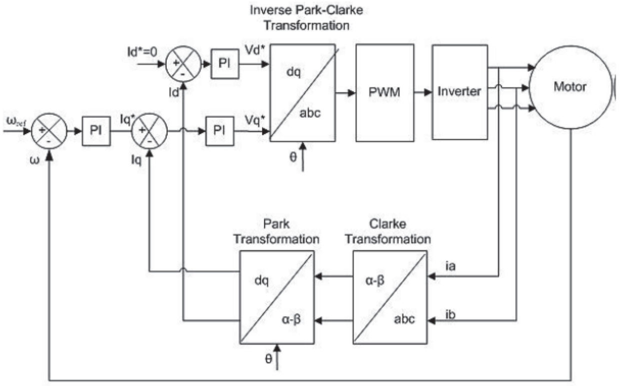

Fig. 3. Basic block diagram of speed control of PMSM

by reducing steady state error, disturbance signal rejection, and relative stability. The system's sensitivity with respect to parameters also decreases. [8]–[10] The transfer function of the PI controller is given by Eq. (10):

$$G_c(s) = K_p + \frac{K_i}{s} \tag{10}$$

The PI controller reduces rise time and minimizes the steady-state error. But peak overshoot, settling time, order, and type of the system will be increased. It functions as a low pass filter. The output equations of the PI and PID controllers are given by Eq. (11) & (12):

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{11}$$

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{12}$$

A command speed ω_{eref} is compared with the motor's speed ω_r and provides the change or error in speed $\Delta\omega$, which is given to the P, PI or PID controller to obtain the command torque component of stator current i_{qref}. [9]–[11] The basic block diagram of the PMSM using vector control strategy is as shown in figure 3. The Simulink model depicting the control strategy employed for Permanent Magnet Synchronous Motor (PMSM) is depicted in Figure 4. The rotating two phase currents i_d and i_q are produced from mathematical modelling of PMSM as shown in figure 5. The characteristic equations of the PMSM building blocks are operated with inverter voltages and produce electromagnetic torque T_e and speed ω_m of the motor. Figure 6 illustrates the experimental setup employed for the speed control of a Permanent Magnet Synchronous Motor (PMSM) using various control strategies.

V. RESULTS AND DISCUSSION

P, PI, and PID speed controller simulations have been run for a three-phase PMSM with an 10 Nm load torque and 100 RPM (10.47 rad/sec) and 200 RPM (2.094 rad/sec) operating speeds. It is evident that the PI controller takes 95 ms to reach the rise time (90 percentage of the command speed), the P controller takes 110 ms, and the PID controller takes 94 ms.

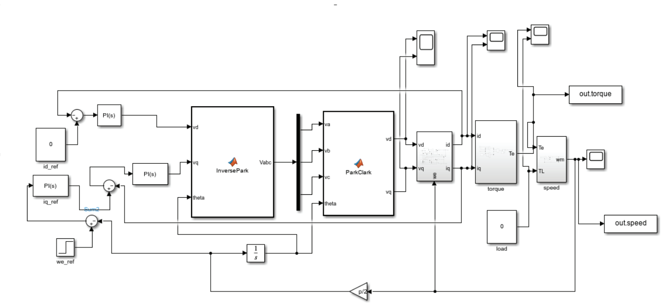

Fig. 4. Simulink model of PMSM

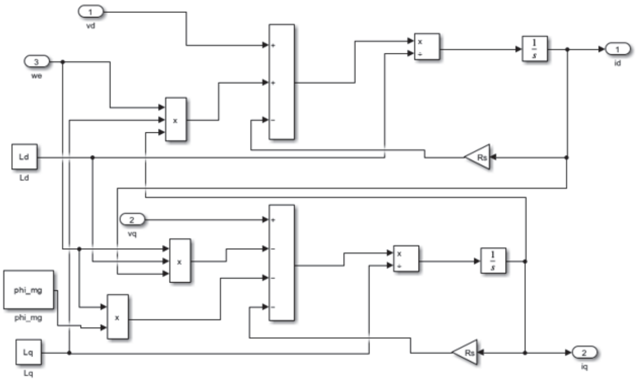

Fig. 5. Simulink model of PMSM i_q and i_d currents

Compared to both P and PID controllers, the PI controller exhibits a better responsiveness. The PI controller significantly outperforms P and PID controllers with a steady state error of 0.01rad/s or 0.0955 rpm, stabilizing the motor speed at a reference speed (with 2 percentage tolerance) of 100 RPM in 2.5s and 200 RPM from 100 RPM in 3s. Compared to PID and P controllers, the PI controller has a slightly higher peak overshoot (8 percentage), but it provides a superior steady state response. However, the steady state error of both P and PID

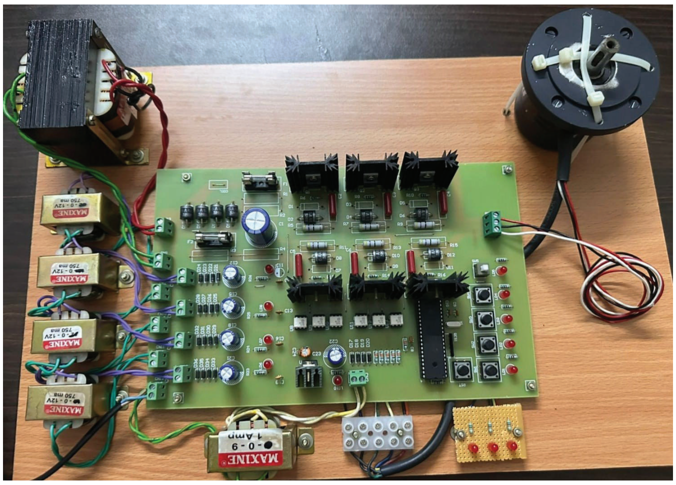

Fig. 6. Experimental setup of PMSM

controllers is greater than 2 percentage. This can be reduced by fine-tuning the parameters more precisely. The depicted figure 7 illustrates the machine speed curve when the Proportional (P) controller is employed as the input controller. It is observed that the rise time associated with this configuration is significantly greater compared to alternative methodologies; however, it concurrently yields superior overshoot and steady-state performance.

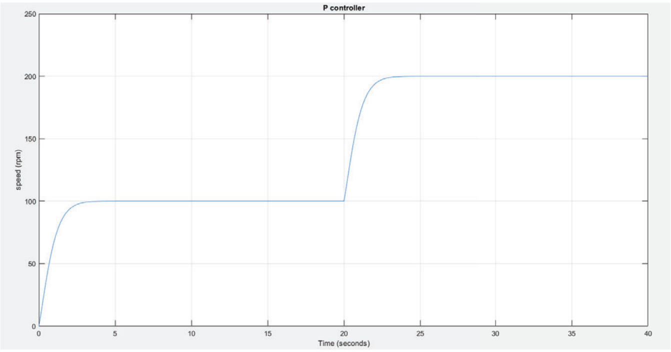

Fig. 7. Speed of the motor using P controller

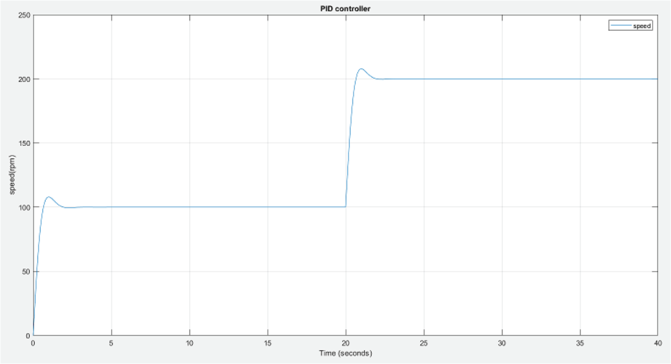

Fig. 8. Speed of the motor using PID controller

The depicted figure 8 portrays the machine speed curve under the influence of a Proportional-Integral-Derivative (PID) controller as the input controller. Notably, the rise time associated with this configuration surpasses that of alternative methods, albeit with an attendant increase in overshot during the initial swing.

The illustrated figure 9 elucidates the machine speed curve under the influence of a Proportional-Integral (PI) controller as the input controller. It is noteworthy that the rise time within this configuration closely approximates that of a Proportional-Integral-Derivative (PID) controller. Furthermore, the observed transient and steady-state responses are commendable, characterized by an steady state error magnitude of less than 2 percentage.

Figure 10 illustrates the Vq and Vd voltages derived from the three-phase voltage source, corresponding to command speeds of 100 and 200 revolutions per minute (RPM).

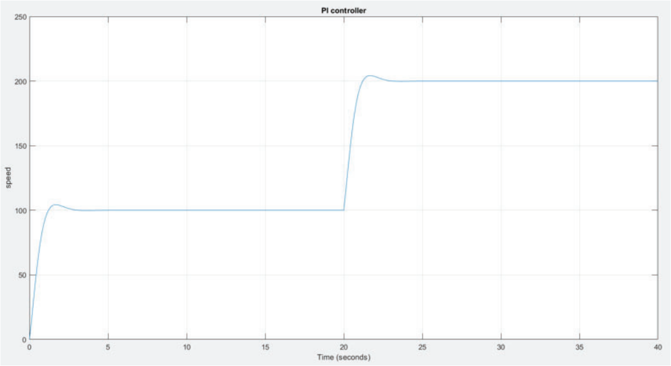

Fig. 9. Speed of the motor using PI controller

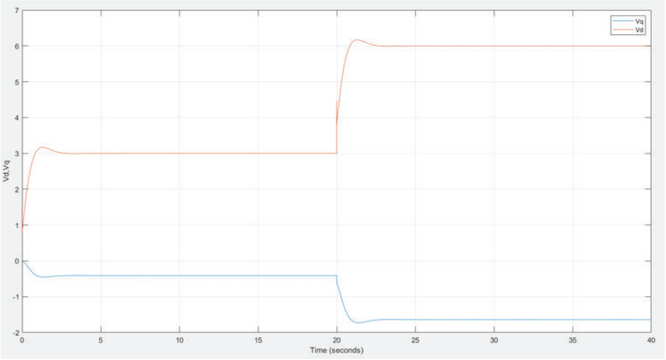

Fig. 10. V_d and V_q voltage wave forms

VI. CONCLUSION

This study develops the mathematical model of a vector controlled PMSM drive with P, PI, and PID controllers for an electric vehicle's propulsion system and presents the simulation results. The findings show that compared to the P and PID controller, the PI controller produces a more reliable tracking response of the command speed with reduced transient and steady-state error. Better performance in rise time is also provided by PI controllers with minimal percentage overshoots. The vehicle can operate smoothly with good static and dynamic performance characteristics when using the PI controller, according to the model's overall output responses.

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