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Investigating the Effect of Vector Control on Permanent Magnet Synchronous Motor Performance Characteristic Using Vector Control Technique

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ABSTRACT

Permanent Magnet Synchronous Motor (PMSM) is an AC synchronous motor whose field excitation is provided by permanent magnets. The permanent magnets are used as the rotor to create constant magnetic flux that operates and locks at synchronous speed. The PMSM has significant advantages that attract the interest of researchers and industries. These include;better thermal performance, higher power density, and simpler in construction when compared to the distrbuted windings. This configuration also helps in reducing the overal resistance of the windings, leading to improved efficiency and performance characteristics of the motor. It has it's usage in electric vehicles, robotics and industrial automation. The Permanent Magnet Synchronous Motor suffers some deficiencies which create some inefficiency to its performance characteristics. Some of these deficiencies include Ripple torque, accurate motion control and load Disturbance compensation. The objective of this paper is to enhance the performance characteristics of PMSM using vector control technique. From the analysis of experimental results obtained, when vector controller was implemented. The reference speed being 1000 RPM, there was a fast dynamic speed response; however there was an overshoot of 180 RPM about 18% of the reference speed. With the load disturbance of the torque at 0.5, the velocity went down to about 510 RPM which is about 49% of the reference speeds, but subsequently track the desired speed within a short time.

Keywords: *Control, Synchronous motor, PMSM, Vector controller.*

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I. INTRODUCTION

A permanent magnet synchronous motor (PMSM) is an electric motor that uses permanent magnets to generate the magnetic field necessary for rotor rotation. PMSMs are known for high efficiency, reliability and precise control. They find applications in various industries, including electric vehicles, robotics and industrial automation. The interaction between the stator and rotor magnetic fields enables efficient energy conversion, making PMSMs popular in scenarios requiring high performance electric drives. In a permanent magnet synchronous motor (PMSM), the rotor contains permanents magnets usually made of rare-earth materials like neodymium. These magnets generate a separate excitation system. The stator, on the other hand, carries windings that are fed with alternating current (AC). The interaction between the magnetic field produced by the stator winding and the permanent magnets on the rotor generates torque that drives the motor. The synchronous nature of the motor implies that the rotor and stator magnetic fields stay in synchronous, leading to efficient power conversion continuously.

Permanent Magnet Synchronous Motors (PMSM) suffer three significant deficiencies, which includes, Ripple Torque, Accurate motion control and Load disturbance compensation. They deficient in speed reference tracking.Another factor affecting Permanent magnet synchronous motors has been the type of controllers used in their controls. This research work therefore tends to bring solution to the above mentioned deficiencies of permanent magnet synchronous motors, thereby enhances the performance of the PMSM.

Many speed controllers use a Proportional Integral and Derivative (PID) control algorithm. It is a controller that is widely used in control processes in industry, which can be attributed to its simplicity of design [1,2]. The Proportional term responds to the current error, the Integral term accounts for past errors over time, and the Derivative term anticipates future errors. These actions are performed simultaneously to bring about correctional control command [3]. This combination helps to fine-tune the control response and improve system performance. In addition to speed control, the speed controller indirectly influences torque. By adjusting the motor current or voltage, it can regulate the torque output of the PMSM, which is crucial in various applications like robotics, electric vehicles, and industrial automation. The speed controller has a fast and accurate dynamic response to changes in the load or operating conditions.

Burkhart [4] stated that Electrical drives have been widely used in several industrial applications for decades, and are still in constant process of advancement for more suitable applications in terms of size, power electronics control and other control techniques. Xiao [5] confirmed that recent advancement in motor drives and control such as permanent magnet synchronous motors comes from their use in the transportation sector, where applications such as aerospace and electric vehicles that require drive systems with higher performance, power density, efficiency and reliability are considered. In harmonic current cancellation method for PMSM drive system using resonant controllers was presented in [6]. It stated that in many applications, PMSMs is predominantly used due to their comparative advantages over other electrical drives. Xiong [7] stated that the control algorithms forPMSM are mainly divided into three categories, namely vector control, direct torque control (DTC), and model predictive control (MPC). Among them, MPC can handle multi-input and Multi-output nonlinear systems with complex constraints and has superior dynamic performance and parameter robustness. Liu [8] stated that vector control, also known as Field-Oriented Control (FOC), is a technique used to control PMSM and AC induction motors(ACIM). Field Oriented Control provides good control capability over the full torque and speed ranges. The implementation of this type of control scheme requires transformation of stator currents from the stationary reference frame to the rotor flux reference frame also known as *d-q* reference frame. From the analysis of Karamanakos [9], vector control strategy was formulated in the synchronously rotating reference frame. Zhang and Wang [10] stated that are permanent-magnet synchronous motors widely used in various applications due totheir simple control, high efficiency, good torque characteristics, and low loss. Xie [11] used data-driven adaptive fractional order PI control for PMSM servosystem with measurement noise and data.

In this paper, a vector control approach is used to enhance the performance of PMSM. Vector controller has the advantage of controlling the magnitude and frequency of the supply voltage and phase. Vector control separates the magnetic flux and the torque component of the current and controls them independently. Vector control can compensate for non- linearity and losses of the motor and can provide fast and accurate speed and torque control, even at low speeds.

II. MATERIAL AND METHODS

1. Modelling PMSM in d-q Rotating Reference Frame

The dynamic equations of a PMSM in the d-q reference frame are given by:

$$V_d = Rs_{id} + {}^{\mathrm{Ld}}\frac{\mathrm{did}}{\mathrm{dt}} - \omega_e Lq_{iq} \tag{1}$$

Where: $(V_d)$and $(V_q)$are the d axis and q axis stator voltages.

$(I_d)$and $(I_q)$are the d axis and q axis stator currents

(R_s) is the stator resistance.

$(L_d)$and $(L_q)$are the d axis and q axis inductances.Φ

(ω) is the electrical angular velocity.

(ϑ_m) is the permanent magnet flux linkage.

Park and Clarke Transformations

To transform the three-phase stator currents to the d-q frame, the Clarke and Park transformations are used.

Clarke Transformation (abc to αβ):

$$\begin{pmatrix} \mathrm{i}_\alpha \\ \mathrm{i}_\beta \end{pmatrix} = \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{pmatrix} \begin{pmatrix} \mathrm{i}_\alpha \\ \mathrm{i}_b \\ \mathrm{i}_c \end{pmatrix} \tag{2}$$

Park Transformation (αβ)to dq:

$$\begin{pmatrix} \mathrm{i}_\alpha \\ \mathrm{i}_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \mathrm{i}_\alpha \\ \mathrm{i}_\beta \end{pmatrix} \tag{3}$$

Where (\theta) is the rotor position

Control Strategy

a. Current Control Loop

The objective is to control the d-axis and q-axis currents. Typically, the d-axis current (i_q) is controlled to regulate the torque

b. PI Controllers for Current Regulation

PI controllers are used for regulating (i _d) and (i_d):

$$V_d^* = K_{pd}(i_d - i_d) + K_{id} \int (i_d^* - i_d)\, dt \tag{4}$$

Where:

$(V_{d^\wedge})$and (V_q^)are the reference voltages for the d and q axes

$(i_d)$and (i_q) are thereference currents for the d and q axes (typically $(i_q = 0)$).

(K_{pq}), (K_{id}), (K_{pq}), and $(K_{iq})$are the PI controller gains.

Inverse Park and Clarke Transformations

The references voltages (V_d) and (V_q) are transformed back to the three-phase system using the inverse park and Clarke transformations.
Inverse park transformation (dqto αβ to abc)

$$\begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} V_d^* \\ V_a^* \end{pmatrix} \tag{5}$$

Inverse Clarke transformationαβ to abc):

$$\begin{pmatrix} V_\alpha \\ V_\beta \\ V_c \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \sqrt{\frac{3}{2}} \\ -\frac{1}{2} & -\sqrt{\frac{3}{2}} \end{pmatrix} \begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} \tag{6}$$

Space Vector Pulse Width Modulation (SVPPWM)

The final step is to apply the calculated three-phase Voltages (V_a), (V_b), (V_c) to the inverter using a technique such as Space Vector Pulse Width Modulation (SVPWM) to control the PMSM.

These steps encapsulate the mathematical formulations involved in the vector control of PMSMs. The core idea is to decouple the torque and flux control by transforming the stator currents and voltages into a rotating reference frame aligned with the rotor flux.

2. Vector Control Model of PMSM in MATLAB

On the MATLAB/Simulink platform, a model of the Vector controlled PMSM is fed from DC supply via an inverter, developed and simulated based on the appropriate equations derived previously. A simulation diagram of the Vector control strategy is shown in Figure 1, in which the Vector control block, inverter block, power supply module, PMSM module, Clark transformation and Park transformation modules to obtain feedback currents of the d and q-axis current are included. Figures 1 to 3 are the Simulink model of the Vector control strategy and Subsystem model of current and speed controllers respectively. The parameters of PMSM, which includes inverter, current and velocity used in the simulation are given below:

PMSM Parameters

Phi = 0.1; % Permanent magnet flux linkage [Wb]
L_d = 0.01; % Stator d-axis inductance [H]
L_q = 0.02; % Stator q-axis inductance [H]
R_s = 0.38; % Stator resistance per phase [Ω]
p = 2; % Number of pole pairs
J_m = 0.1e-3; % Rotor inertia [kg*m^2]

Dm = 1e-3;   % Rotor damping [N*m/(rad/s)]

Inverter Parameters

Vdc = 100;   % DC voltage [V]
fc = 10e3;   % Carrier Frequency [Hz]
T_s = 1/fc/100; % Sampling time [sec]

Current controllers of dq-axis (PI controller)

%$L_d/R_s = \ 0.0263[sec]$;
% $L_q/R_s \ = \ 0.0526[sec]$;
% Target response time constant: 1e-3[sec]
$W_c\underline{c}$ = $1e^3$; % $Targetresponsefrequency\ [rad/s]$
Kp_id = wc_c*Ld; % d-axis proportional gain
Ki_id = wc_c*Rs; % d-axis integral gain
Kp_iq = wc_c*Lq; % q-axis proportional gain
Ki_iq = wc_c*Rs; % q-axis integral gain
% Tcc = 100e-6;   % Sample time of current control [sec]

Velocity controller (PI controller)

% Jm/Dm = 0.1[sec];
% Target response time constant: 0.02[sec]
wc_s = 50;   % Target response frequency [rad/s]
Kp_s = 0.0014;   % Velocity proportional gain
Ki_s = 0.041;   % Velocity integral gain
% Kp_s = wc_s*Jm;   % Velocity proportional gain
% Ki_s = wc_s*Dm;   % Velocity integral gain
% Tsc = 1e-3;   % Sample time of velocity control [sec]

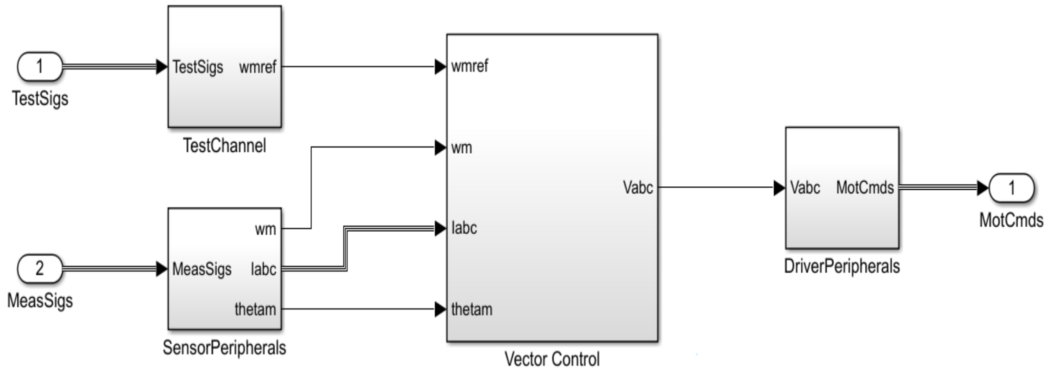

Figure 1: Simulink model of the Vector control strategy

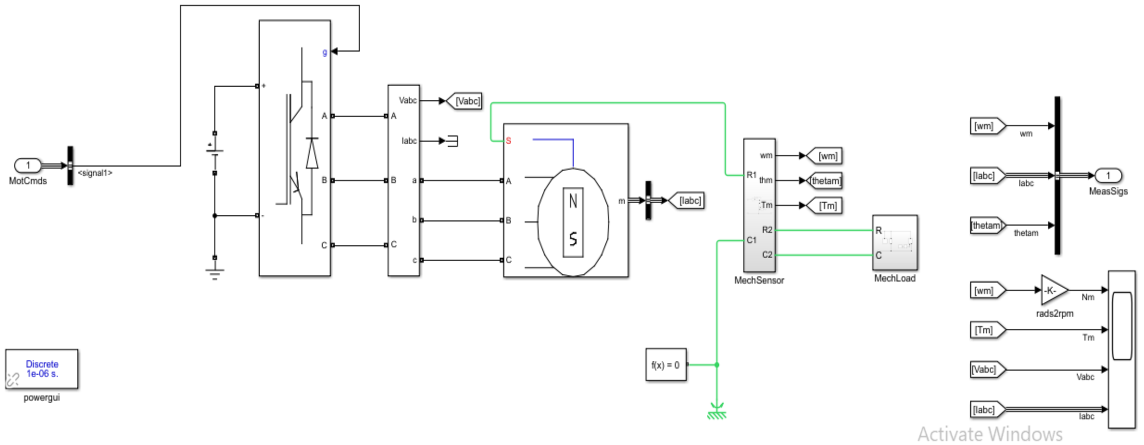

Figure 2: Subsystem model of the PMSM

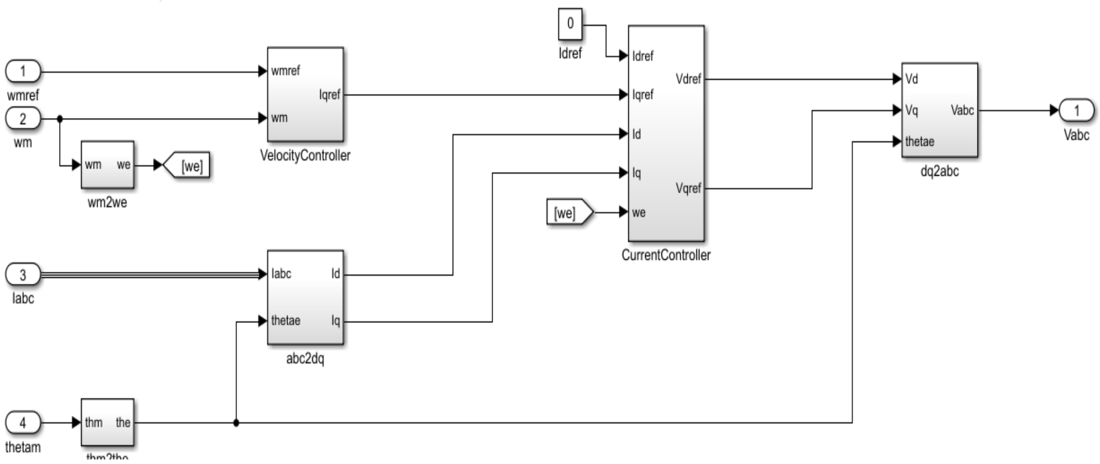

Figure 3: Subsystem model of current and velocity controllers

III. RESULTS AND DISCUSSION

This section presents the simulation results of the vector control in terms of speed response. The simulation results show that the vector control has fast dynamic speed response. Figure 4 shows the waveforms speed, torque, current and voltage for the vector control. The speed response plot of the PMSM based vector control is shown in Figure 5.

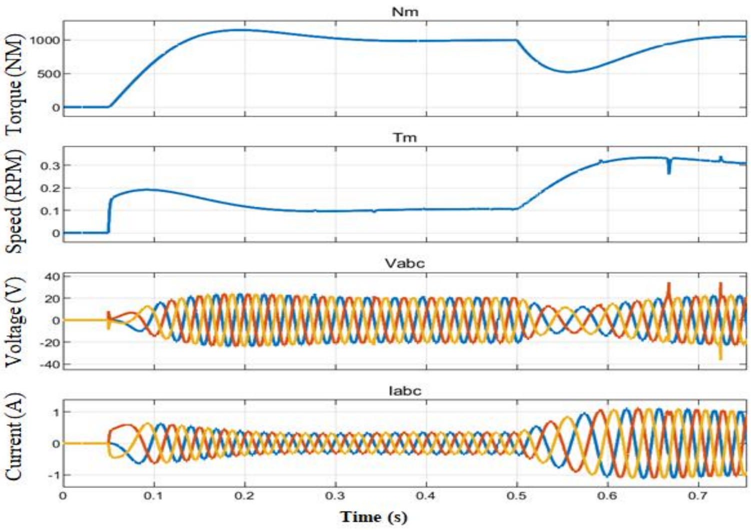

Figure. 4: Waveforms of speed, torque, current and voltage for the vector control

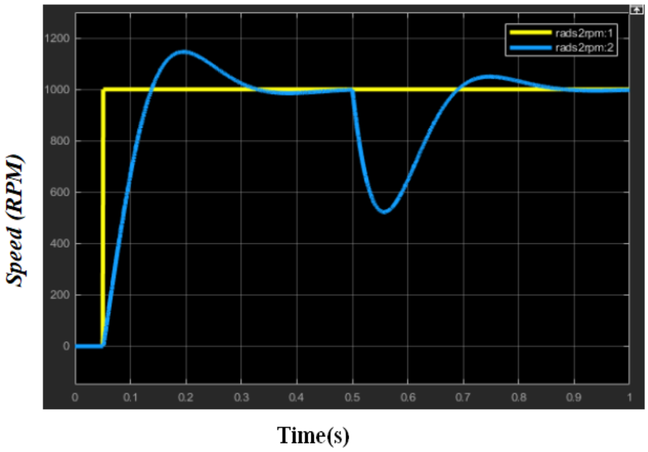

Figure 5: Reference speed vs actual motor speed for vector control.

Here we can see that the velocity has overshoot from 1000 RPM to 1,180 RPM, but it tracks to the target velocity. And, when there was disturbance of the load torque at t=0.5sec, the velocity goes down to about 510 RPM as shown in Figure 5. The performance of vector control is very good in the ideal case but is greatly affected by variations in the load parameters. Also from the graph of waveforms of speed, torque current and voltage for vector control, it can be seen that with the reference speed of 1000 RPM, the velocity of vector control has an overshoot of 180 RPM, about 18% of the reference speed, but it tracks the target speed. And, when the load disturbance torque at 0.5sec was caused, the speed fall down to about 510 RPM as can be seen from Figures 4 and 5. Generally, when reference speed was 1000 RPM, the vector controller has 1,180 RPM, with overshoot of 180 RPM, 18% of referenced speed.

IV. CONCLUSION

A MATLAB/Simulink simulation model is developed to verify the enhanced PMSM using vector control. The PMSM motor model and the IGBT model come from the SimPower Systems library of SIMULINK. Six separate IGBTs with fly-wheeling diode are used as switches, driven by DC link voltage of 400 V. A three-phase AC permanent magnet synchronous motor is used, which is made by nominal torque of 2.4 Nm. The performance of the PMSM using vector control was evaluated in terms of speed overshoot, torque ripple and current waveforms stability. Simulation result shows that the speed and torque responses of the vector control were enhanced such that after the introduction of the disturbance torque at t= 0 s, the system operation did not deteriorate endlessly but the controller adjust its speed response as fast as possible within a short while and maintained the setpoint speed.

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