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Ripple torque lessening in space vector pulse width modulation based direct torque control of permanent magnet synchronous motor drive

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Abstract— in this work, the ripple reduction in torque using space vector pulse width modulation based direct torque control of permanent magnet synchronous motor by employing the predictive current to estimate the flux magnitude is discovered. To lessen the ripple in current, a model-based predictive current is used to estimate the magnitude of current applied for flux estimation. Two control plans are applied to show the viability of the framework. MATLAB/Simulink is used to develop a model of PMSM and simulate the system considering different control algorithm. Simulation is performed for both simple current control and SVPWM-DTC control scheme. The result of the simulation indicates that the torque and current ripple is less for SVPWM-DTC with considerable initial overshoot.

Keywords— *permanent magnet synchronous motor (PMSM), space vector pulse width modulation (SVPWM-DTC), current prediction, current control, Torque-ripple*

1. Introduction

Permanent magnet synchronous motor (PMSM) has structure that appropriate for the cooling framework as the rotor part has no winding that causes a loss. The direct torque control is proposed as the best alternative for PMSM because of quick unique reaction and less calculation time. Be that as it may, the downside of DTC control is a variable switching that makes more misfortune and numerous scientists suggest the space vector pulse width regulated based direct torque control (SVPWM-DTC). The torque predictive control (TPC) where the reference voltage is gotten from the numerical connection between the change in torque and stator motion has less torque ripple contrasted with SVPWM-DTC [1]. Examination of the impact of the parameter variation on PMSM operation has done in [2]. The optimal current control greatly affects torque extent and ripple. Torque is partitioned into DC esteem, ripple and cogging torque. The extent of flux produced from magnet diminishes with growing temperature. Definite estimation of the flux of permanent magnet greatly affects the control and operation of PMSM. Due to the flow of large current in the winding or high temperature, the flux will pulsate and creating ripples torque [3].

Other PMSM huge drawback is the ripple torque which is produced to due to current harmonics, change in flux and cogging torque. Torque ripple minimization strategy that depends on harmonic current compensation is proposed in [4]. The inductances of PMSM change nonlinearly due to



saturating. By feeding the current which produce the torque that negates the ripple torque due to cogging and current harmonics the level of a torque can be minimized. Extended Kalman filter estimation of flux and compensation of nullifying current for ripple component, taking current and flux as a state variable is covered in [5]. Based on flux obtained from estimation and current, the compensation current to refute a ripple torque due to non-sinusoidal flux in PMSM is added to a feedback current to eliminate the ripple component. Six pulse two-level quick dc bus voltage controls has high power thickness as it applies all out voltage. This empowers the motor to follow a wide scope of MTPA activity [6]. In the traditional DTC, the voltage determination depends on the two-level signal produced from flux hysteresis controller, a three-level signal created from torque controller, flux control band, torque control band and flux angle. DTC with a high sampling frequency and low starting speed can overcome a ripple which is a sound problem in classical DTC. Self-controlled DTC uses a components of flux to determine the active status of the voltage while the torque is used to determine used to decide the in active voltage selection. Constant switching DTC use a constant switching period which easy to implement but produce high ripple [7]. PMSM experience the ill effects of parasitic impedances that come to present during the operation. Space vector based DTC that utilization both positive and negative sequence for generation of reference voltage is more effective to lessen ripple in current and torque when the motor is operating in unbalanced mode [8]. Torque developed from permanent magnet motor is a related to a sin of an angle between stator flux and rotor flux [9]. A distinctive class of DTC is applied to get a quick unique reaction in PMSM control. In the technique where the goal is to regulate flux and torque, the voltage vector is chosen using the lookup table [10].

2. PMSM Model and Axis Transformation

Synchronous frame model and coordinate transformation for translating one coordinate to other is used to represent machine mathematically.

$$i_{abcs} = \begin{bmatrix} \cos(\theta_r) & -\sin(\theta_r) \\ \cos(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) \end{bmatrix} i_{dqsr} \quad (1)$$

$$i_{dqsr} = \frac{2}{3} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ -\sin(\theta_r) & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) \end{bmatrix} i_{abcs} \quad (2)$$

$$i_{qds} = \begin{bmatrix} \cos(\theta_r) & \sin(\theta_r) \\ -\sin(\theta_r) & \cos(\theta_r) \end{bmatrix} i_{qds}^r \quad (3)$$

$$v_{qds} = \begin{bmatrix} \cos(\theta_r) & \sin(\theta_r) \\ -\sin(\theta_r) & \cos(\theta_r) \end{bmatrix} v_{qds}^r \quad (4)$$

$$\lambda_{qs}^r = L * i_{qs}^r \quad (5)$$

$$\lambda_{ds}^r = L * i_{ds}^r + \lambda_f \quad (6)$$

$$v_{qs}^r = R * i_{qs}^r + L \frac{d}{dt}(i_{qs}^r) + \omega(\lambda_{ds}^r) \quad (7)$$

$$v_{ds}^r = R * i_{ds}^r + L \frac{d}{dt}(i_{ds}^r) - \omega * \lambda_{qs}^r \quad (8)$$

$$i_{qs}^r = \frac{1}{L} \int (v_{qs}^r - R * i_{qs}^r - \omega * \lambda_{ds}^r) dt \quad (9)$$

$$i_{ds}^r = \frac{1}{L} \int (v_{ds}^r - R * i_{ds}^r + \omega * \lambda_{qs}^r) dt \quad (10)$$

The mutual flux in the air gap is the totality of rotor and stator component of a flux. Magnitude of mutual flux in air gap is obtained by taking the sum of d axis and q axis flux.

$$\lambda_m = \sqrt{(\lambda_{qs}^r)^2 + (\lambda_{ds}^r)^2} \quad (11)$$

$$i_s = \sqrt{i_{ds}^r^2 + i_{qs}^r^2} \quad (12)$$

$$\begin{matrix} i_{qs}^r \\ i_{ds}^r \end{matrix} = i_s \begin{bmatrix} \sin(\delta + \theta_r) \\ \cos(\delta + \theta_r) \end{bmatrix} \quad (13)$$

$$\delta = \tan^{-1}\left(\frac{i_{qs}^r}{i_{ds}^r}\right) \quad (14)$$

$$\omega_m = \frac{1}{J} \int (T_e - T_l - B * \omega_m) dt \quad (15)$$

$$\omega = \frac{P}{2} * \omega_m \quad (16)$$

$$\theta_r = \int \omega dt \quad (17)$$

Electromagnetic torque developed from PMSM is highly related to the angle between rotor flux and stator flux. Fast dynamics is obtained by altering the angle stator flux speed.

$$T_e = 1.5 * P * \lambda_f * \frac{\lambda_m}{L} * \sin \delta \quad (18)$$

$$\Delta T_e = \frac{dT_e}{dt} = 1.5 * P * \lambda_f * \frac{\lambda_m}{L} * \cos \delta * \dot{\delta} \quad (19)$$

$$T_e = 1.5 * P * \lambda_f * i_{qs}^r \quad (20)$$

Required speed and speed deviation from required magnitude is provided to an adder to get torque command. The magnitude of d axis current is programmed based on the magnitude of speed error. The from torque command, q axis current can be obtained easy by manipulating it mathematically [11]. The magnitude of VSI output three phase voltages and synchronous rotating frame amplitude of the voltage is calculated as shown below when the Ta, Tb and Tc are the switching signal which can possess value of 0 or 1.

$$v_{abcs} = \frac{v_{dc}}{3} \begin{bmatrix} 2T_a - T_b - T_c \\ 2T_b - T_a - T_c \\ 2T_c - T_b - T_a \end{bmatrix} \quad (21)$$

This voltage is supplied to the motor and, it can be expressed in an equivalent way using the following equation in a rotating synchronous frame.

$$v_{dqs}^r = \frac{2}{3} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ -\sin(\theta_r) & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) \end{bmatrix} v_{abcs} \quad (22)$$

The flux estimation for the cut-off frequency of varying as a function of speed is indicated as shown below when μ is a constant value that ranges from 0.1 to 0.5 and current and voltage is the vector components in alpha-beta co-ordinate.

$$\omega_c = \mu \omega_s \quad (23)$$

$$\omega_s = \frac{\psi_\alpha(v_\beta - R * i_\beta) - \psi_\beta(v_\alpha - R * i_\alpha)}{\psi_\alpha^2 + \psi_\beta^2} \quad (24)$$

$$\widehat{\psi}_\alpha = (\overline{v}_\alpha - R * \overline{i}_\alpha) \left(\frac{1}{s + \omega_c} \right) (1 - \mu * \text{sgn}(\omega_s)) \quad (25)$$

$$\widehat{\psi}_{\beta} = (\overline{v}_{\beta} - R * \overline{i}_{\beta}) \left(\frac{1}{s + \omega_c} \right) (1 - \mu * \text{sgn}(\omega_s)) \quad (26)$$

As flux angle and torque is the input for DTC control it can be effortlessly obtained shown below.

$$\theta_{\psi_s} = \tan^{-1} \left(\frac{\psi_{s\beta}}{\psi_{s\alpha}} \right) \quad (27)$$

$$T_e = 1.5 * P * (\psi_{\alpha} * i_{\beta} - \psi_{\beta} * i_{\alpha}) \quad (28)$$

3. General structure of the system

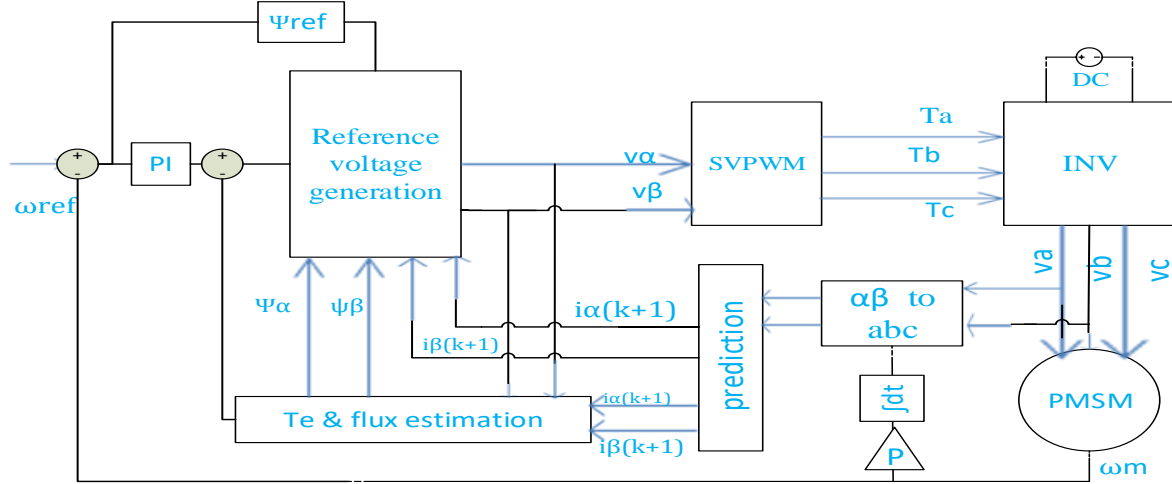


Figure 1 PMSM Control Using SVPWM-DTC with Predictive Current

3.1 Flux and voltage estimation

The magnitude of the flux is evaluated utilizing equation 25 and 26. Filter is used in place of an integrator. Torque is obtained by using equation 28 while reference magnitude of torque, which is the input for flux and voltage, is obtained from the yield of a controller as shown above on figure 1. The magnitude of reference flux is gotten from equation 18. Adjusting the equation 18, the extent of reference flux is assessed as appeared underneath by equation 29.

$$\psi_{sref} = \frac{T_e * L}{1.5 * P * \lambda_f * \sin \delta} \quad (29)$$

The reference voltage for generation of switching signal using SCPWM is obtained from rate of lux change plus voltage on the resistive component.

$$\begin{aligned} \psi_{\alpha ref}^* &= \begin{cases} |\psi_{\alpha ref}| * \cos(\theta_{\psi_s} + \Delta\theta_{\psi_s}) - |\psi_{\alpha}| * \cos \theta_{\psi_s} \\ |\psi_{\beta ref}| * \sin(\theta_{\psi_s} + \Delta\theta_{\psi_s}) - |\psi_{\beta}| * \sin(\theta_{\psi_s}) \end{cases} \end{aligned} \quad (30)$$

$$\begin{aligned} v_{\alpha} &= \begin{cases} \frac{\psi_{\alpha ref}^*}{T_s} + R * i_{\alpha}(k) \\ \frac{\psi_{\beta ref}^*}{T_s} + R * i_{\beta}(k) \end{cases} \end{aligned} \quad (31)$$

3.2 Current prediction

To have better dynamics, current magnitude is predicted from the previous current, sampling time and motor parameters.

$$i_{\alpha}(k+1) = \left(1 - \frac{R * T_s}{L}\right) * i_{\alpha}(k) + T_s * \omega * i_{\beta}(k) + \frac{T_s * v_{\alpha}(k)}{L} \quad (32)$$

$$i_{\beta}(k+1) = \left(1 - \frac{R * T_s}{L}\right) * i_{\beta}(k) - T_s * \omega * i_{\alpha}(k) - \lambda_f * \omega * T_s + \frac{T_s * v_{\beta}(k)}{L} \quad (33)$$

3.3 Motor parameter and constant used

PMSM model is developed in Matlab/Simulink 2018. For showing the effectiveness of the suggested system, result of simulation for proposed system and current control of PMSM is compared. All parameter were given in SI unit.

Table 1 Motor parameter and constant used

Parameter	Magnitude	Parameter	Magnitude
Resistor	0.001	Pole	8
Inductance	0.1	Magnet flux	0.3055
Maximum current	1.7	Torque	4
Controller bandwidth	1000	Vd	128
Frequency	1000	μ	0.3
J	0.024		

4. Result of simulation and analysis

The simulation is performed for two control schemes of PMSM, i.e. current control, and SVPWM-DTC. Flux estimation for SVPWM-DTC based on voltage and current. To reduce the estimation error predictive current method is applied to estimate current based on the sampling time, model parameter, and previous current magnitude.

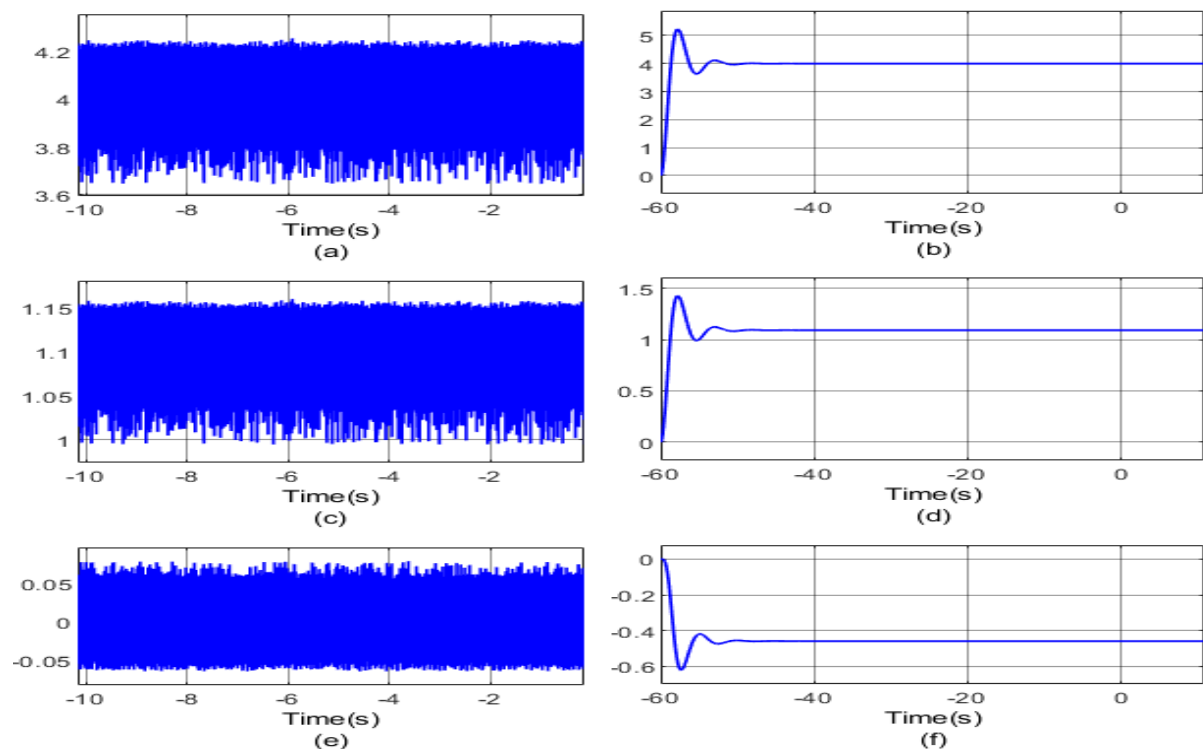


Figure 2 Simulation result of PMSM control: (a) shows the torque with current control, (b) shows the torque with SVPWM-DTC, (c) shows the q-axis current with current control (d) shows the q-axis current with SVPWM-DTC, (e), shows the d-axis current with current control, (f), shows the d-axis current with SVPWM-DTC

From the Figure 2 (a) and (b) the magnitude of a torque is oscillating between 3.6 to 4.2 and approximately 4 for current control and SVPWM-DTC respectively. And again from Figure 2 (c) and (d) the magnitude of q axis current is depicted. From this picture the range of oscillation of current is high for current control compared to SVPWM-DTC.

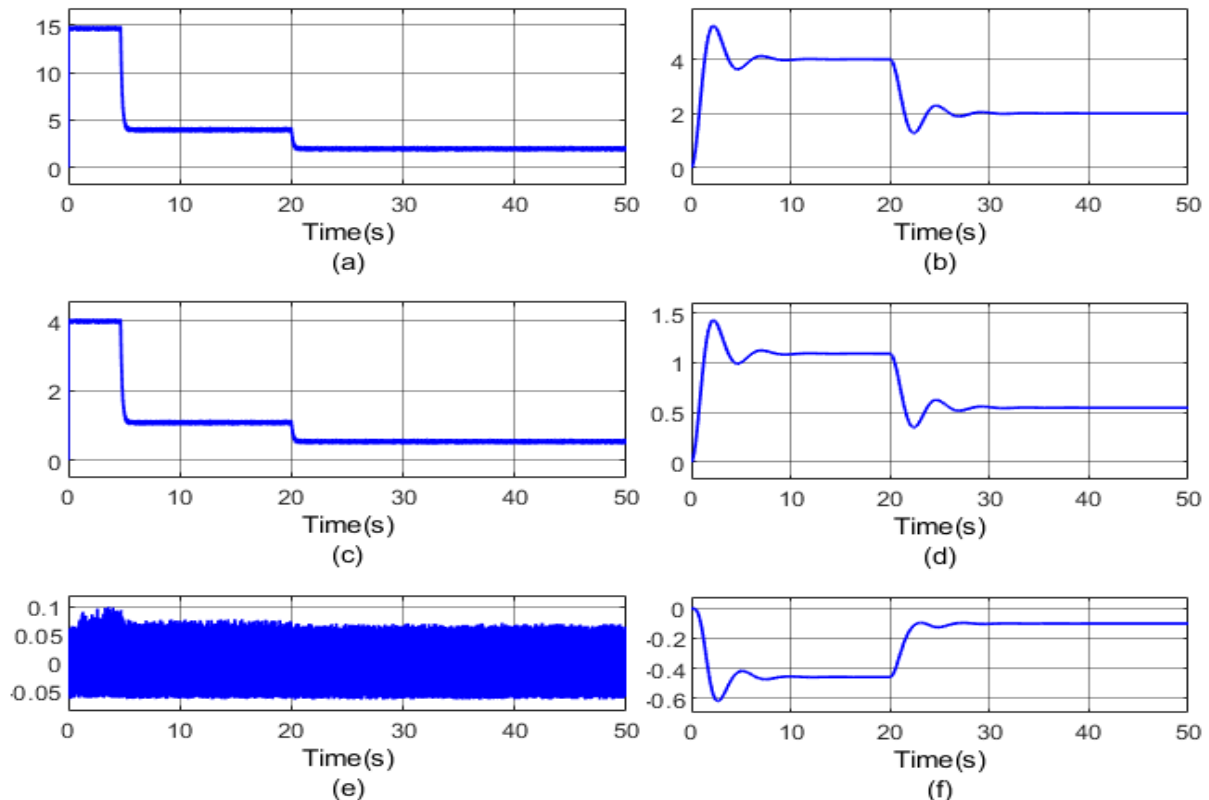


Figure 3 Simulation result of PMSM control: (a) shows the torque with current control, (b) shows the torque with SVPWM-DTC, (c) shows the q-axis current with current control (d) shows the q-axis current with SVPWM-DTC, (e), shows the d-axis current with current control, (f,) shows the d-axis current with SVPWM-DTC

From Figure 3 (a) and (b) the magnitude of a reference torque changed from 4 Nm to 2 Nm at 20 seconds. The magnitude of torque ripple oscillates between 1.8 to 2.1 for Figure 3 (a) after 20 seconds, whereas for Figure 3 (b) the torque is approximately 2 Nm, with a high initial overshoot of 25%, which means it reduces to 1.5 for the final value of 2 Nm.

5. Conclusion

Matlab 2018 is used for modelling system component like PMSM, inverter and control algorithm. Two control schemes i.e. current control and SVPWM-DTC are applied to control the drive system and simulation is performed. From the simulation result depicted in Figure 2 and the magnitude of ripple is less for the system which is controlled by SVPWM-DTC. To reduce the ripple for SVPWM-DTC the predictive current is used to estimate the magnitude of current which has an indirect effect on flux and torque ripple. Again from Figure 3, the torque is changed from the reference value of 4 to 2 at a time of 20 seconds; the simulation indicates the SVPWM-DTC has less ripple torque compared to current control with considerable initial overshoot.

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