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Torque Ripple Reduction in Permanent Magnet Synchronous Motor using Predective Control Scheme

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Abstract:
In Permanent magnet synchronous motor, high performance motion control is mostly carried out using Field Oriented Control and more recently Direct Torque Control is being used. The main advantages of direct torque control (DTC) technique of permanent magnet synchronous motor (PMSM) are eliminating the current controller and quicker dynamic response. But, high torque and stator flux ripples are the drawbacks in the technique. In order to overcome these drawbacks, a Torque Predictive Control (TPC) scheme is proposed. It is a mathematical approach to minimize the torque ripple. It uses the relationship between stator flux, stator voltage and incremental torque. It decides the proper direction of voltage vector usto drive torque error to zero. Normally, sensors are used to measure the speed and rotor position. Sensors increase the complexity with reduced reliability. In order to overcome these problems, speed is extracted from the d axis output voltage of synchronous current regulator in the proposed scheme. Simulation results are presented for the proposed TPC scheme to showbetter torque response with less ripples.

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1. Introduction

Nowadays, Permanent magnet synchronous motors are more popular and widely used in industrial applications. The advantages of PMSMs are high efficiency and reliable, high power factor and power density, good dynamic performance with high torque/inertia ratio.However, the main disadvantage of PMSM is the torque pulsation. Torque pulsation produces the mechanical vibration and acoustic noise. The torque produced by a PMSM can be divided into three components:

1) Mutual torque, which is due to the interaction of the rotor field and stator currents;

2) Reluctance torque, which is due to rotor saliency;

3) Cogging torque, which is due to the existence of stator slots.

Each component can contribute to higher harmonics in total torque, i.e., to torque ripple.

In order to minimize torque ripple, many techniques based on both motor design and control schemes have been proposed in literature [3]. A wide variety of control methods

dependon the application of Fourier analysis to obtain the Fourier coefficients of current harmonics. The basic goal of these control schemes is to control the current so that the ripple is cancelled out.This is known as harmonic injection method [5].

The shape of the injected current is not uniquely determined and an additional constraint is often added to minimize ohmic losses [1]. However, this work has nothing to do with the harmonics in control system associated with measurement noises, switching harmonics and voltage harmonics supplied by the power inverter which constitute the major source of unavoidable harmonics in PMSM. It is favorable that the currents and voltages provided to the motor terminals, are perfect sinusoidal wave and do not include harmonic components.

An inverter output filter system for PWM motor drives can reduce harmonics of PMSM [7]. This method is composed of conventional RLC filter cascaded with an LC trap filter tuned to the inverter switching frequency. The scheme shows some effectiveness in reducing switching harmonics, but however, very large circulating current between inverter output and filter elements is required to reshape the motor terminal voltage which violate current limitation of the inverter.

An Iterative learning control (ILC) is utilized for torque/speed ripple minimization of a brushless surface-mounted PMSM drive [6]. However, the ILC scheme has its own limitation for real-time applications, particularly at high-speed operating conditions. Moreover, they used a PI controller for the inner control loop to generate pulse width-modulated (PWM) control signals.

A filter topologies has been used in PMSM which consists of an insulated-gate bipolar transistor Active Filter and two RLC filters [2]. Filter topologies are beneficial to reduce torque ripple and current harmonic noises. It has some disadvantages like tuning problem and relatively expensive hardware.

A Torque Predictive Control scheme is used to reduce the torque ripple effectively by use of stator flux and incremental torque. It is a mathematical approach to minimize the torque ripple. It decides the proper direction of voltage vector u_s for driving the torque error to zero. Normally, sensors are used to measure the speed, whereas in the proposed system, speed will be calculated fromthe d axis output voltage of synchronous current regulator. It is easily implemented.

II.TORQUE PREDICTIVE CONTROL SCHEME

A.PMSM MATHEMATICAL MODEL

The motor has to be modeled in order to analyse a PMSMvariable speed driving system. For modelling the PM motor,assumptions are given as follows,

1) The neutral point is not connected

2) Iron saturation is assumed negligible

3) There are no eddy currents or core losses

4) Only the fundamental wave of the air-gap field is considered for the calculation of the inductances

In the analysis, the stationary reference frame is used. Theelectrical dynamics of the PMSM drive can be described interms of vectors by the following equationsVoltage equation:

$$U_s = R\, i_s + \frac{d}{dt}\psi_s \quad (1)$$

Flux equation

$$\Psi_s = L i_s + \psi_r \quad (2)$$

where $\mathbf{u}_s = [u_{s\alpha} u_{s\beta}]t$, $\mathbf{i}_s = [i_{s\alpha} i_{s\beta}]t$, $\boldsymbol{\psi}_s = [\psi_{s\alpha} \psi_{s\beta}]t$, and $\boldsymbol{\psi}_r = [\psi_r \cos\theta \psi_r \sin\theta]^t$. the d- and q-axis inductances are equal for a surface-mounted PM motor, and they are both represented by symbol L. Motor

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electromagnetic torque is a function of the stator flux and the stator current. It can be expressed as

$T_e = p_n \boldsymbol{\psi}_s \times \mathbf{i}_s$(3)

B. *RELATIONSHIP OF VOLTAGE VECTORS WITH THE MOTOR TORQUE*

For the analysis of TPC, it is necessary to obtain a discrete time representation of the motor torque whose value is updated at every sampling interval. This is achieved based on motor mathematical equations. From (3), the dynamic of the motor torque can be obtained as

$$\frac{d}{dt}T_e = P_n\left(\frac{d}{dt}\psi_s \mathrm{x}\, i_s + \psi_s \mathrm{x} \frac{d}{dt} i_s\right)(4)$$

It is shown that the increment of the torque is a function ofstator flux vector $\boldsymbol{\psi}_s$and stator current vector $\mathbf{i}_s$. From (1) and(2), dynamic equations are obtained as follows

$$\frac{d}{dt}\psi_s = u_s - Ri_s(5)$$

$$\frac{d}{dt}i_s = \frac{1}{L}\left(u_s - Ri_s - \frac{d}{dt}\psi_r\right)(6)$$

Substituting (5) and (6) into (4), the torque dynamic can be derived as

$$\frac{d}{dt}T_e = \left(\frac{P_n}{L}\psi_s \mathrm{x}\, u_s + p_n\, u_s \mathrm{x}\, i_s - \frac{R_s}{L}T_e - \frac{p_n}{L}\psi_s \mathrm{x} \frac{d}{dt}\psi_r\right)$$

(7)

By knowing the values of vectors $\boldsymbol{i}_s$, $\boldsymbol{\psi}_s$, and $\boldsymbol{\psi}_r$, it is possible to control the motor torque toward a desired value by controlling voltage vector $\boldsymbol{u}_s$. Suppose that during one DSP control cycle T_s, non-zero voltage vector $\boldsymbol{u}_s$is applied to the motor with a time duration of T_k. Based on (7), the impact of this voltage vector to the motor torque can be derived as

$$\Delta T_e' = \left(\frac{P_n}{L}\psi_s \mathrm{x}\, u_s + p_n u_s \mathrm{x}\, i_s - \frac{R_s}{L}T_e - \frac{p_n}{L}\psi_s \mathrm{x} \frac{d}{dt}\psi_r\right)T_k(8)$$

For the rest time of the control cycle $T_s - T_k$, a zero voltage is applied; hence, the torque variation is deduced as

$$\Delta T_e'' = \left(-\frac{R_s}{L}T_e - \frac{p_n}{L}\psi_s \mathrm{x} \frac{d}{dt}\psi_r\right)(T_s - T_k)(9)$$

The sum of (8) and (9) is the total torque increment in a full DSP control cycle T_s, is given by$\Delta T_e = \left(\frac{P_n}{L}\psi_s \mathrm{x}\, u_s + p_n\, u_s \mathrm{x}\, i_s\right)T_k$

$$\left(-\frac{R_s}{L}T_e - \frac{p_n}{L}\psi_s \mathrm{x} \frac{d}{dt}\psi_r\right)T_s(10)$$

Equation (10) gives the relationship between voltage vector***us*** and torque increment ΔT_e. In this equation, the values of stator and rotor fluxes are calculated based on the measurement of the stator current and the rotor speed. With calculated voltage vector $\boldsymbol{u}_s$from this equation, TPC strategy can accurately control the motor torque.

If the output voltage vector ***us*** of the inverter satisfies (10), the torque error can be nullified in the next cycle. In order to simplify the control structure, in the TPC strategy, $\boldsymbol{u}_s$is set with a fixed magnitude, which is equal to the magnitude of the basic voltage vector of the inverter. If the magnitude of voltage vector $\boldsymbol{u}_s$is too small, it cannot assure a quick torque control response. On the other hand, the bigger the voltage i_s, the bigger the torque ripples will be. Finally, by changing the direction of voltage vector $\boldsymbol{u}_s$, the increment of the torque and the stator flux can be properly controlled. According to the mathematical model, the motor stator flux can be processed as an integration of voltages. Neglecting the voltage drop on stator resistance, the increment of the stator flux vector can be calculated as

$$\Delta\psi_s = T_k(u_s - R_s i_s) = T_k u_s(11)$$

With the above equation, the voltage vector in (10) can be substituted by a stator flux error. The value of $\Delta T_e$and$\Delta\psi_s$are acquired from torque and flux hysteresis controllers. The calculation error of $\Delta\psi_s$due to the approximation will introduce disturbance to the decision of the voltage vector control angle.TPC strategy in also uses the stator flux vector $\boldsymbol{\psi}_s$as a positioning reference. The problem is that the calculation error of vector $\boldsymbol{\psi}_s$will make the positioning become less accurate.

In order to overcome these problems, a TPC strategy is proposed in this paper. As is known, the position angle of vector $\boldsymbol{\psi}_r$is proportional to the value of rotor position angle, and this value can be acquired through a rotor position sensor. Taking vector $\boldsymbol{\psi}_r$as a position reference, the control voltage can be more accurately oriented. To achieve this target, the relationship between $\boldsymbol{u}_s$and$\boldsymbol{\psi}_r$should be analyzed first. Rearranging the first part on the right side of (10), we have,

$$\left(\frac{P_n}{L}\psi_s \text{x}\, u_s + p_n\, u_s \text{ x}\, i_s\right)T_k = \left(\frac{P_n}{L}(\psi_s - Li_s)\text{ x}\, u_s\right)T_k$$

$$=\frac{P_n}{L}\psi_r \text{ x}\, u_s T_k (12)$$

Substituting (12) into (10) gets

$$\Delta T_e = \frac{P_n}{L}\psi_r \text{ x}\, u_s T_k + \left(-\frac{R_s}{L}T_e - \frac{p_n}{L}\psi_s \text{x}\frac{d}{dt}\psi_r\right)T_s$$

(13)

The calculation of ΔT_ein (13) is simplified, compared with (10). By knowing the magnitude of voltage vector $\boldsymbol{u}_s$, the new voltage control angle λ can be derived as follows:

$$\lambda = arcin\left(\frac{\Delta Te\left(\frac{R_s}{L}T_e - \frac{p_n}{L}\, L\psi_s \text{x}\frac{d}{dt}\psi_r\right)T_s}{p_n|\psi_r||T_k x u_s|}\right)$$

(14)

The purpose of angle λ is to decide the proper direction of voltage vector $\boldsymbol{u}_s$for driving the torque error $\Delta T_e$to zero. This angle λ is the phase difference between inverter voltage ***us*** and rotor flux $\boldsymbol{\psi}_r$. This angle decides the switching sector of the inverter.

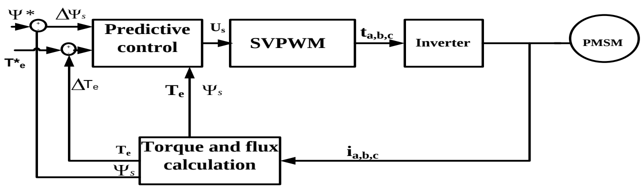

Fig. 1 Block diagram of Torque Predictive Control scheme

Fig. 1 shows block diagram of proposed Torque Predictive Control scheme. It consists of two control loops that focus on the performance of the motor torque and flux, respectively. In the proposed scheme, the motor torque and the stator flux are compared to their reference values. The differences are then sent to the predictive control block to calculate the control angle of voltage vector $\boldsymbol{u}_s$according to (14). Finally, the control voltage $\boldsymbol{u}_s$is generated from a two-level voltage source inverter to drive the permanent magnet synchronous motor, where the SVPWM method is used to control the switching of the inverter. The calculation of the control strategy is not complicated and can be carried out within one controlcycleT_s.

C. SENSORLESS SPEED ESTIMATION

The sensorless control techniques are highly reliable and reduce cost of the drive. In sensorless control the reliability is achieved by eliminating the hall sensors and feedback devices traditionally located inside the motor housing. Sensorless control technology eliminates the need for these devices, which in turn reduce motor size, cost, and improves overall reliability. In the steady state, motor voltage equations in the rotor synchronous frame are time invariant, and they contain the

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speed information. By substituting $U_d$andU_q with stationary frame axes current and voltage, motor speed can be expressed with measurable variables, and its value can be calculated directly. Thecalculation is direct and easy.The speed is estimated by processing output voltages of d axis synchronous proportional-integral(PI) current regulator in high speed range, and the current with a constant magnitude.The information of speed can be extracted from the block diagram. The estimated speed is used to find out the torque reference with the help of PI controller.

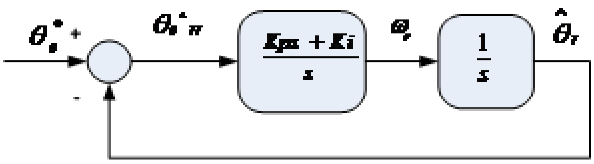

Fig. 2 Block diagram of speed extraction

Where

$\theta_e{}^{\wedge}{}_{rr}$ = rotor position error

ω_r = rotor speed

Ki is the integral gain

$\theta^{\wedge}{}_r$ = rotor position

Kp is the proportional gain;

IV SIMULATON BLOCK FOR TORQUE PREDICTIVE CONTROL SCHEME

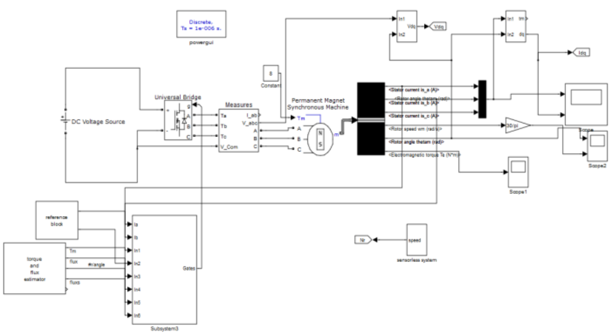

Fig. 3 Simulation diagram of Torque Predictive Control scheme

IV SIMULATON RESULTS

The Torque Predictive Control scheme is simulated by MATLAB/Simulink. Torque error is eliminated by the proper selection of voltage control angle. Fig. 3 shows the electromagnetic torque output response at load torque 8 Nm.

From the figure it is inferred that the torque ripple is minimized 0.02%. Torque ripple factor = (peak to peak value/rated torque)*100. Fig. 4 shows the stator current response at load torque 8Nm. It has somewhat high starting overshoot value. It can be eliminated by proper tuning. Fig. 5 shows the stator direct and quadrature current axis response at load torque 8 Nm.

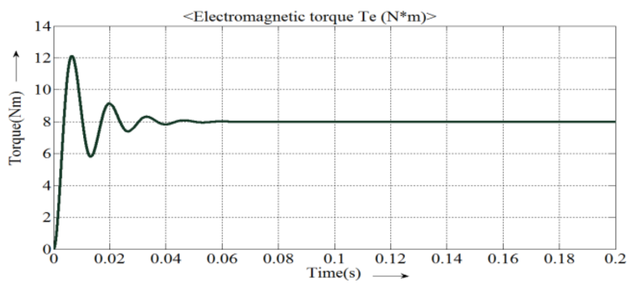

Fig.4 Simulation result of the motor Torque at load torque 8Nm

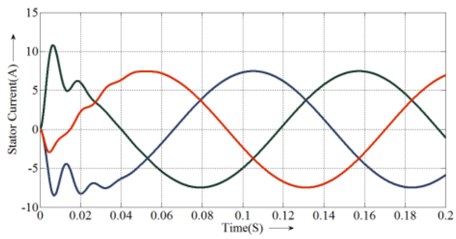

Fig.5 Simulation result of three phase stator current response

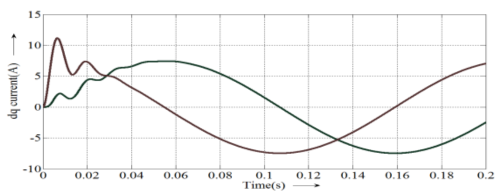

Fig.6 Simulation result of direct and quadrature current response

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Simulation results shows the satisfactory performance of the torque response. It has no ripple as comparedto torque ripple reduction technique such as Iterative learning control and Harmonic injection method.

V.CONCLUSION

The Torque Predictive Control Scheme is simulated.Results are discussed in this paper. In this control scheme,Voltage control angle is calculated using stator flux and incremental torque to decides the proper selection of the voltage vector. It is a simple method to reduce the torque ripple. It is a mathematical approach and does not need any algorithm.It has no ripple compared totorque ripple reduction technique such as Iterative learning control and Harmonic injection method. The simulation results have demonstrated the feasibility of the TPC system with low torque ripple, and sinusoidal behaviour of the stator current.

Appendix

Parameters of the permanent magnet synchronous motor

R	0.9585ohm
P	8
L	0.00525H
Speed	2000rpm
Torque	8 Nm
Voltage	300V

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