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Comparative Study on Direct Torque Control of Interior Permanent Magnet Synchronous Motor for Electric Vehicle

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Abstract: Comparative studies on several direct torque control (DTC) strategies of interior permanent magnet synchronous motor (IPMSM) for electric vehicles (EVs) are discussed in details, namely basic DTC, DTC combined with space vector modulation (DTC-SVM), and deadbeat DTC (DB-DTC). These DTC strategies are reviewed, meanwhile dynamics and steady-state performance are analyzed and compared. Simulations of a 20kW IPMSM for EVs are carried out for comparison studies including: ripple of torque and stator flux, sensitivity to machine's parameter, computational complexity, and total harmonic distortion of stator current. The results can be used as guidance for application of IPMSM to EVs and others.

Keywords: Direct torque control, flux, interior permanent magnet synchronous motor, electric vehicle, deadbeat, observer, simulation.

1. INTRODUCTION

With the increasing demand of living comfort, automobile gets more and more utilized for individual and public transportation because of its convenience. But, accompanying vast fuel consumption and environmental pollution become more serious. Automobile companies focus on electric vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel-cell vehicles. Among these, electric vehicles get the most attraction in recent years for its only convenient and rechargeable battery power supply and simple driver control structure. Interior permanent magnet synchronous motor (IPMSM) has some merits of high power density, high efficiency, good reliability, low torque ripple and wide range of speed regulation, which make it much fitter for electric vehicles driving than other general electric machines such as induction motor (IM), brushless DC motor (BLDC), and switch reluctance motor (SR) as presented by Chan (1996).

To promote performance of IPMSM, current vector control (CVC) is the most widely used approach to regulate the torque of IPMSM as presented by Macminn (1991) and Morimoto (1994). When using CVC, stator current, rather than torque and stator flux, is the closed-loop controlled variable. In CVC of IPMSM, voltage space vectors of the inverter are the only input for closed-loop control of stator current. The stator current dynamics will affect torque and stator flux performance. For EVs, IPMSM driver will receive torque command from car controller with different operating mode. The torque, precisely controlled or not, will affect car dynamics and human comfort. Therefore, the torque open-loop control of CVC is not extremely suitable for IPMSM control of EVs.

Direct torque control (DTC) has closed-loop control both of torque and stator flux, which was firstly proposed for IM by Takahashi and Noguchi (1986) and Depenbrock (1988). At present, DTC has become a powerful and widely used control strategy of AC machines. The dq axis vector decoupling of field oriented control (FOC) is replaced by two hysteresis controllers of DTC, which meets very well with the on-off operation of power transistors of inverter. DTC of IPMSM was firstly presented by Zhong (1997). DTC has some virtues of both control strategy framework and driver materials. Comparing with FOC, DTC does not require any coordinate transformation and space vector modulation. Furthermore, DTC also does not require rotator position sensor which is essential for FOC. DTC is natively sensorless leading to simplified implementation and lower cost. DTC has comparable steady and dynamic torque performance with FOC. Additionally, DTC has low sensitivity to parameters vibration of electric machine. But, the disadvantages of basic DTC is also obvious: torque and flux ripple, deteriorated performance at low speed, and variable switching frequency of inverter.

For the defects of basic DTC, much works have been made over the past few decades. DTC combined with space vector modulation (DTC-SVM), separately proposed by T. G. Habetler (1992) for IM and Zhang (2004) for IPMSM, is to achieve constant switching frequency of inverter as well as to

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obtain the desired torque and stator flux with little ripple by synthesizing an appropriate voltage space vector through SVM, which is more accurate than that of basic DTC to compensate the error of desired and actual stator flux.

DTC with deadbeat control, namely DB-DTC, is proposed for IM by Lee (2002) and Kenny (2003). Theoretically, DB-DTC can reach the desired torque in one control period with synthesized voltage space vector. The dynamics and steady-state error of DB-DTC are better than basic DTC and DTC-SVM even at low switching frequency, which is necessary for high power machines used for EVs. DB-DTC for IPMSM proposed by Lee (2011) contains a discrete time flux observer for accurate torque and stator flux control. Moreover, a dq rotating reference frame current observer is designed to eliminate the sampling delay caused by digital control implementation.

In this paper, basic DTC, DTC-SVM and DB-DTC will be comparatively evaluated through simulations with various criteria. The comparison results will be used as guidance for application of IPMSM to industry and electric vehicles.

2. IPMSM MODEL

DTC is realized on base of IPMSM model. Expressions of IPMSM in rotating dq reference frame are listed as follows

$$\begin{cases} u_d = R_s i_d + \dfrac{d\lambda_d}{dt} - \omega_e \lambda_q \\ u_q = R_s i_q + \dfrac{d\lambda_q}{dt} + \omega_e \lambda_d \end{cases} \quad (1)$$

$$\begin{cases} \lambda_d = L_d i_d + \lambda_{PM} \\ \lambda_q = L_q i_q \end{cases} \quad (2)$$

where u_{dq} and i_{dq} are stator voltage and current; R_s is stator resistance; L_d and L_q are d-axis and q-axis stator inductance, respectively; λ_{dq} is stator flux; ω_e is electrical rotor angular velocity; λ_{PM} is permanent magnet flux. The torque of IPMSM is

$$T_e = 1.5p\left(\lambda_d i_q - \lambda_q i_d\right) \quad (3)$$

where p is the number of rotator pole pairs.

3. DTC STRATEGY

3.1 Basic DTC

For AC machines, the torque is proportional to vector product of stator flux $\vec{\lambda}_s$ and rotator flux $\vec{\lambda}_r$. For IPMSM, rotator flux is induced by permanent magnet, then $\lambda_r = \lambda_{PM}$, which is almost a constant. The angle velocity of rotator varies little when voltage space vector affects on stator windings during one sample period, so the torque is only decided by stator flux vector. By applying appropriate voltage space vector, basic DTC can control the magnitude and angle of stator flux to obtain desired torque. The framework of basic DTC is shown in Fig.1.

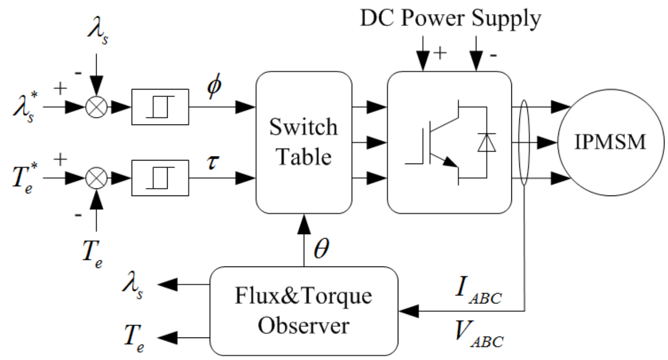

Fig. 1. Framework of basic DTC.

IPMSM stator winding currents are measured by hall current sensors, and its voltages are calculated by inverter switch state. The actual stator flux and torque are calculated by flux and torque observer. The actual stator flux and torque are compared with the reference values in two separate hysteresis controllers. The hysteresis controllers are two-level comparator whose outputs are labelled with ϕ and τ. If the actual value is less than down bounds of the reference value, the comparator outputs true (also 1) meaning that the selected voltage space vector should increase the actual value. On the other side, if the actual value is larger than up bounds of the reference value, the comparator outputs false(also 0) meaning that the selected voltage space vector should decrease the actual value. According to the outputs of two hysteresis controllers and the stator flux position, an optimal voltage space vector will be selected and applied to stator windings to minimize the error of stator flux and torque in each control period. The selection of optimal voltage space vector is referred to Table 1. In this table, θ is the section of stator flux position.

Table 1. Switch table of basic DTC

ϕ	τ	θ					
		1	2	3	4	5	6
1	1	u_6	u_2	u_3	u_1	u_5	u_4
	0	u_5	u_4	u_6	u_2	u_3	u_1
0	1	u_2	u_3	u_1	u_5	u_4	u_6
	0	u_1	u_5	u_4	u_6	u_2	u_3

The parameters of IPMSM are listed in Table 2. The performance of basic DTC is shown in Fig.2. The bound of torque hysteresis control is 5N.m, and that of stator flux is 0.05Wb. Fig.2 demonstrates torque and stator flux are limited within bounds of the two separate hysteresis controllers. The ripple of torque and stator flux is controllable. The dynamic response with step-up torque reference is about 0.15ms.