Direct Torque Control of Permanent Magnet Synchronous Machine

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To my parents,

Xiang Li and Xiping Cao

Abstract

This thesis presents the direct torque control (DTC) on the permanent magnet synchronous machine (PMSM). The effects of zero voltage vectors and non-zero voltage vectors on the PMSM DTC drive are analyzed. New switching tables are developed. The control of the amplitude of stator flux, torque angle and torque of the PMSM DTC drive are discussed. The voltage vector selection strategy of the PMSM DTC drive is given. All of these are verified by simulation and experimental results.

Due to the voltage drop on stator resistance and the move of rotor flux vector the application of zero voltage vectors decreases the amplitude of stator flux and torque. Thus the use of zero voltage vectors to increase the amplitude of stator flux and decrease torque can't satisfy the control of stator flux. For the PMSM, the application of zero voltage vectors can't produce the negative torque. When the PMSM operates as a brake, the use of zero voltage vectors introduces stator current ripple. Based on the effect of zero voltage vectors, a switching table using zero voltage vectors for the PMSM DTC drive is proposed and the advantages of the use of zero voltage vectors are given.

The switching table of the PMSM DTC drive is based on the viewpoint that the change of torque is always consistent with the change of torque angle. It holds true only at the dynamic state. When the PMSM DTC drive is at the steady state, the effect of the change of the amplitude of stator flux on torque can't be neglected comparing with the change of torque angle. When torque angle is higher, the change of torque isn't always consistent with the change of torque angle and the switching table causes torque ripple. Using the three-phase and two-phase connection, a two-level voltage source inverter (VSI) can generate 12 non-zero voltage vectors of 30° between each other. And we divide voltage vector plane into 12 sectors of 30° between each other. Thus there are 12 non-zero voltage vectors to be used in every sector. Based on the effect of these voltage vectors on torque in a sector, the PMSM DTC drive should select $V_{120^{\circ}}$ to decrease the amplitude of stator flux and increase torque and select $V_{300^{\circ}}$ to increase the amplitude of stator flux and decrease torque. A novel switching table for the PMSM DTC drive is proposed. Simulation results show the novel switching table can suppress torque ripple comparing with the conventional switching table, but when torque angle is higher, it will also cause torque ripple. In simulation the commutation torque ripple due to the additional use of the two-phase connection is neglected, but experimental results show it degrades the control performance in practice.

As the DTC is the hysteresis control, the voltage vector selection strategy as the hysteresis control rule is essential to the control performance. The control of the amplitude of stator flux, torque angle and torque of PMSM are shown in the following. For the control of the amplitude of stator flux, if the angle between stator flux vector and the applying voltage vector is within (-90°, 90°), the voltage vector increases the amplitude of stator flux and if the angle is within (90°, 270°), the voltage vector decreases the amplitude of stator flux. For the control of torque angle, if the angle between stator flux vector and the applying voltage vector is within (0°, 180°), the voltage vector increases torque angle and if the angle is within (180°, 360°), the voltage vector decreases torque angle. For the control of torque of SPMSM, if the angle between rotor flux vector and the applying voltage vector is within (0°, 180°), the voltage vector increases torque and if the angle is within (180°, 360°), the voltage vector decreases torque. For the control of torque of PMSM, if the angle between stator flux vector and the applying voltage vector is within ($\lambda-\theta$, $180^{\circ}+\lambda-\theta$), the voltage vector increases torque and if the angle is within ($180^{\circ}+\lambda-\theta$, $360^{\circ}+\lambda-\theta$), the voltage vector decreases torque. The effect of voltage vector on the amplitude of stator flux, torque angle and torque of PMSM is proportional to the amplitude of voltage vector and the applying period. The voltage vector selection area of the PMSM DTC drive and a simplified voltage vector selection strategy are given. The technology of space vector modulation (SVM) is used to generate the applying voltage vector. Comparing with the PMSM DTC drive using the switching table, the voltage vector selection strategy and the SVM are used to generate the switching signals instead of the switching table and the continuous stator flux position and torque angle information instead of stator flux sector information are needed. Simulation and experimental results show comparing with the switching table, the voltage vector selection strategy can decrease the ripples in stator current and torque, fix the switching frequency of the VSI and the PMSM DTC drive can work at higher load situation.

Two methods to start the PMSM FOC/DTC drive are discussed. The two-step pre-fixed method is easy to implement, but as the rotation direction is arbitrary when the rotor is fixed to the given position, it can't be used in some applications. The SPWM open-loop control method is an easy way to start the motor, but it will increase the calculation burden to implement the SPWM control and for the DTC using the voltage model to estimate stator flux, it will introduce the vibration when the DTC is switched on to control the motor.

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