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Minimization of torque ripple of direct-torque controlled induction machines by improved discrete space vector modulation

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Abstract

In this paper, discrete space vector modulation (DSVM) technique for induction machine drives is developed, and then a fuzzy logic direct torque control (DTC) scheme based on the proposed DSVM technique is presented. In DSVM technique, new voltage vectors are synthesized by applying three standard voltage space vectors for three equal time intervals at each sampling period. Rearranging the sequence of the three voltage space vectors does not change final synthesized voltage vectors, but has an influence on torque ripple. By comparing torque waveforms in one sampling period, an analysis is carried out to determine the influence. Based on the analysis, new switching tables used in DSVM-DTC are defined. In the switching tables, the three components of each synthesized voltage vector are arranged in optimized sequence. Finally, a fuzzy logic controller is designed to select synthesized voltage vectors. Its control rules are established based on the proposed switching tables. The proposed scheme is verified by simulations. Simulation results show that a reduction of torque ripples is achieved in a whole speed range.

Keywords: Direct torque control; Discrete space vector modulation; Fuzzy logic controller; Induction machine

1. Introduction

In high-performance variable-speed drive applications for induction machines, there are two most popular control strategies: field-oriented control (FOC) and direct torque control (DTC) [1,2]. Both of them can decouple the interaction between flux and torque control, and provide good torque response in steady state and transient operation conditions. Unlike field-oriented control, direct torque control does not require coordinate transformation and any current regulator. It controls flux and torque directly based on their instantaneous errors [3]. In spite of its simplicity, direct torque control is capable of generating fast torque response [4]. In addition, direct torque control minimizes the use of machine parameters [5], so it is very little sensible to the parameters variation.

One of the disadvantages of conventional DTC is high torque ripple [6]. Several techniques have been developed to reduce the torque ripple. One of them is duty ratio control method. In duty ratio control, a selected output voltage vector is applied for a portion of one sampling period, and a zero voltage vector is applied for the rest of the period. The pulse duration of output voltage vector can be determined by a fuzzy logic controller [7]. In Ref. [8], torque-ripple minimum condition during one sampling period is obtained from instantaneous torque variation equations. The pulse duration of output voltage vector is determined by the torque-ripple minimum condition. These improvements can greatly reduce the torque ripple, but they increase the complexity of DTC algorithm.

An alternative method to reduce the ripples is based on space vector modulation (SVM) technique [9,10]. At each cycle period, a preview technique is used to obtain the voltage space vector required to exactly compensate the flux and torque errors. The required voltage space vector can be synthesized using SVM technique. The torque ripple for this SVM-DTC is significantly improved. However, it requires calculating several complicate equations online, and it depends on more machine parameters. Casadei et al. [11,12] presented a new DTC scheme using discrete space vector modulation (DSVM) technique. It is a control system able to generate a number of voltage vectors higher than that

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used in conventional DTC scheme. The increased number of voltage vectors allows the definition of more accurate switching tables. The DSVM-DTC achieves a sensible reduction of torque ripple, without increasing the complexity of conventional DTC.

As an intelligence method, fuzzy control does not need the accurate mathematic model of the process to be controlled, and uses the experience of people's knowledge to form its control rule base. Fuzzy logic controllers have been used in direct torque control systems in the past few years. In Refs. [13–15], a fuzzy logic controller is used to select voltage vectors in conventional DTC. In parameter estimation applications, a fuzzy logic stator resistance estimator is reported in Ref. [16]. It can estimate changes in stator resistance due to temperature change during operation. For duty ratio control method, a fuzzy logic controller is used to determine the duration of output voltage vector at each sampling period [7,17]. These fuzzy logic controllers can provide good dynamic performance and robustness.

In this paper, DSVM technique for induction machine drives is developed. By optimizing the sequence of selected voltage space vectors in each sampling period, new switching tables are defined. Furthermore, a fuzzy logic controller used in DSVM-DTC is designed to select synthesized output voltage vectors. Its control rules are established based on the proposed switching tables. The remainder of this paper is organized as follows. DTC principle is described in Section 2. In Section 3, torque ripples in DSVM-DTC are analyzed and the optimized switching tables are defined. The design of the fuzzy logic controller is presented in Section 4. Simulation results of the proposed scheme are given and discussed in Section 5. Finally, conclusions are summarized in Section 6.

2. Direct torque control principle

In an induction machine model, stator flux space vector can be written in terms of stator voltage space vector and stator resistance voltage drop

$$\vec{\psi}_s = \int (\vec{v}_s - R_s \vec{i}_s)\,dt \tag{1}$$

where $\vec{\psi}_s$ is stator flux space vector, $\vec{v}_s$ stator voltage space vector, $\vec{i}_s$ stator current space vector, and R_s stator resistance.

If time interval is sufficiently short, neglecting the stator resistance voltage drop, Eq. (1) is rewritten as

$$\Delta \vec{\psi}_s = \vec{v}_s\ \Delta t \tag{2}$$

It shows that the applied voltage space vector produces a stator flux variation which has the same direction of the voltage space vector.

For calculation, in a stationary d–q reference frame, the electromagnetic torque of an induction machine is usually estimated as follows:

$$T_e = \tfrac{3}{2} P(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \tag{3}$$

where P is the number of pole pairs, ψ_{ds} and ψ_{qs} are d- and q-axis components of $\vec{\psi}_s$, i_{ds} and i_{qs} are d- and q-axis components of $\vec{i}_s$.

Another useful electromagnetic torque equation is expressed as

$$T_e = \frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} |\vec{\psi}_s|\,|\vec{\psi}_r| \sin\theta \tag{4}$$

where L_s and L_r are stator and rotor self-inductance, L_m is mutual inductance, $\vec{\psi}_r$ is rotor flux space vector, and θ the angle between stator and rotor flux space vector, called torque angle.

The magnitudes of stator and rotor flux space vector are kept constant by applying proper voltage space vectors. At the same time, the phase angle of the stator flux space vector can be rapidly changed by applying voltage space vectors according to Eq. (2). However, the rotor flux space vector changes slowly compared to the stator flux space vector, and it can be assumed to be constant. This results in the rapid change of the torque angle. It follows from Eq. (4) that the electromagnetic torque can be rapidly changed by changing the torque angle in required direction. In summary, torque can be controlled by voltage space vectors.

The output of a three-phase voltage source inverter (VSI) has 8 possible voltage vectors, including 6 non-zero voltage vectors (V1–V6) and 2 zero voltage vectors (V0, V7). The lines connecting the ends of the 6 non-zero voltage vectors constitute a hexagon. According to the positions of the non-zero voltage vectors, the d–q plane is divided into six sectors. The voltage vectors and the sectors are shown in Fig. 1.

It is assumed that the stator flux space vector is in sector 1, and the angular speed direction is counter-clockwise, as

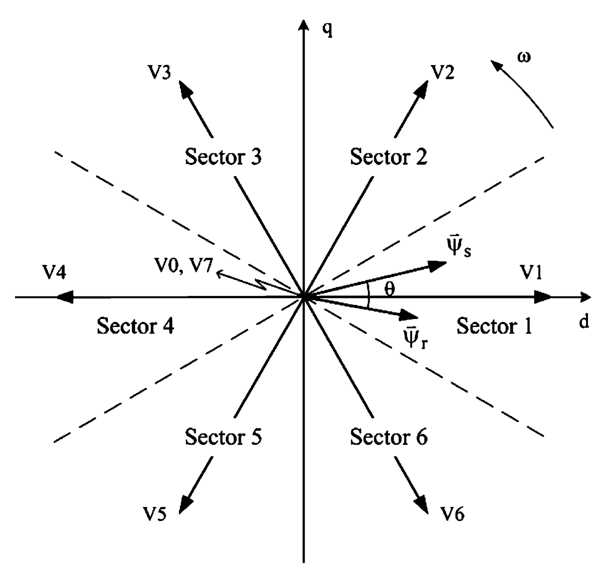

Fig. 1. Eight VSI voltage vectors and six sectors.