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Speed control of switched reluctance motors taking into account mutual inductances and magnetic saturation effects

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ABSTRACT

This paper deals with the speed control of switched reluctance motor (SRM) drives taking into account the effects of the mutual inductances between two adjacent phases and the effects of the magnetic saturation of the core. To overcome the problems commonly associated with single-phase excitation, a nonlinear SRM model, which is suitable for two-phase excitation and which takes into account the effects of mutual inductances between two adjacent phases and the magnetic saturation effects, is considered in the design of the proposed controllers. A feedback linearization control scheme and a sliding mode control scheme are designed for this motor drive. The proposed controllers guarantee the convergence of the phase currents and the rotor speed of the motor to their desired values. Simulation results indicate that the proposed controllers work well and that they are robust to changes in the parameters of the system and to changes in the load torque.

1. Introduction

Switched reluctance motor drives have been receiving renewed attention as attractive candidates for many applications. For example, SRMs are widely used in high performance servo applications, such as the aerospace industry, and other industrial applications, such as electric vehicles and robotics. Combining the unique features of an SRM with its relatively simple and efficient power converter leads to a variable speed motor drive which users prefer in many applications to AC or DC motor drives. The main advantages of an SRM drive are: (1) its simplicity and its low-cost machine construction; this is due to the absence of rotor windings and permanent magnets, (2) the simplicity of the associated unipolar converter, (3) its fault tolerant operation, (4) its rugged behavior and large torque output over a very wide speed range. On the other hand, torque ripples, acoustic noise and rotor position sensing requirements are the main disadvantages of the SRM drive.

The switched reluctance motor is a doubly salient machine with independent phase windings on the stator and a solid laminated rotor. The stator windings (on diametrically opposite poles) are connected in series to form one phase of the motor. Fig. 1 shows a four phase switched reluctance motor with eight stator poles and six rotor poles (a typical 8/6 SRM). When a stator phase is energized (i.e., a pair of diametrically opposite stator poles are excited) the most adjacent rotor pole-pair is attracted towards the energized stator in order to minimize the reluctance of the magnetic path. This excitation produces a torque regardless of the direction of the current in the phase winding. By energizing consecutive phases in succession, it is possible to develop a constant torque in either direction of rotation. The reader can refer to references [1,2] and the references therein for more details on SRMs.

Usually, SRM drives operate in the magnetic-flux-saturation region so that high torque-to-mass ratios can be realized. Hence, magnetic saturation is a very important key to the high-performance operations of SRM drives. High performances can hardly be achieved by using conventional linear controllers, because linearizing the system dynamics around an operating point and designing linear controllers is generally not sufficient to achieve the high dynamical performances required for high performance drives. Moreover, the nonlinearity arising from the high saturation of the magnetic characteristics complicates the design of the control algorithms for such motors. Thus, the modeling of the nonlinear magnetic characteristics and the establishment of good SRM drive models are crucial for the design, performance prediction, and control of SRM drives [3–5]. Therefore, it is necessary to take the system nonlinearities into account and design feedback control laws that compensate for these nonlinearities and also compensate for the uncertainties on the parameters of the system.

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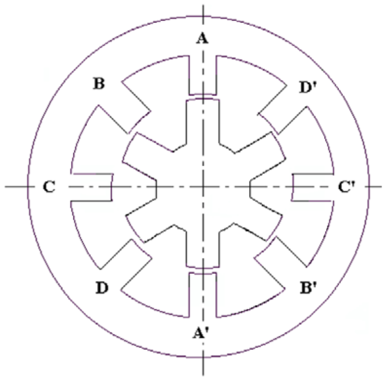

Fig. 1. The cross-section of an 8/6 SRM.

Several nonlinear control techniques have been developed for the control of electrical motor drives. For example, the feedback linearization control technique, the sliding mode control, adaptive control, optimal control, neural control, fuzzy logic have been used to control motor drives. Some of these techniques have been applied to SRM drives. Control of the sum of the squares of the phase currents to minimize torque ripples was proposed in [6]; also, the authors applied a sliding mode controller to the speed control loop to compensate for the low frequency oscillations on the torque output. Although the mutual inductance effects were included in [6], the modeling and simulation of the SRM were accomplished for operations in the linear region of its magnetic characteristics. In reference [7], an approach to reduce the torque ripple while controlling the speed of an SRM was presented. A neural network is used to estimate the generated torque of the SRM; this network is trained off line using data acquired from both the linear region and the saturation region. The main drawback of this approach is the use of a motor data obtained using the finite element method to train the neural network torque estimator. In addition, this method does not consider the effects of mutual inductances between the phases during commutations.

In order to obtain high dynamical performance from an SRM drive, torque distribution functions were proposed in the literature to minimize torque ripples during commutation. In Refs. [8–11], the basic idea was to distribute the desired torque to two adjacent phases during commutation using a specified torque distribution functions. The researchers in [12] proposed a linear decrease of the outgoing phase and a linear increase of the incoming phase during the commutation interval to obtain a high performance drive. In [13], a torque distribution function that minimizes the rates of change of currents over the commutation interval was proposed. In some of the above mentioned control schemes, an ideal inductance profile was assumed. However, none of these controllers considered the effects of mutual inductances during commutation. The effects of mutual inductances and the possibility of two-phase excitation were mentioned in [14–18]. However, no control schemes were suggested to overcome the effects of mutual inductances.

A novel dynamic model for the SRM which is suitable for two-phase excitation control studies and which takes into account the effects of mutual inductances was proposed in [19]. A torque distribution function which reduces the rates of change of currents and which compensates for the effects of mutual couplings and the magnetic saturation was also presented. In addition, a control scheme which is based on linearizing and decoupling the mathematical nonlinear SRM model was proposed.

The main objective of this paper is to investigate the development of nonlinear control schemes that can achieve high dynamical performances for the speed regulation of SRM drives taking into account the effects of the mutual inductances between two adjacent phases and the effects of the magnetic saturation of the core. A model which is suitable for two-phase excitation and which takes into account the effects of the mutual inductances between two adjacent phases and the effects of the magnetic saturation of the core is adopted in this paper. Two nonlinear speed controllers, which take into account the coupling and the nonlinearity in the current loop, are proposed for the SRM drive. Simulation results indicate that the proposed controllers work well and that they are robust to changes in the parameters of the system and to changes in the load torque. Moreover, the proposed control schemes are compared to a linearizing PI current controller motivated by the work [19] which was based on linearizing and decoupling the dynamics of the currents in the mathematical nonlinear SRM model.

The paper is organized as follows. The model of the SRM is presented in Section 2. A feedback linearization controller and a sliding mode controller are proposed in Sections 3 and 4, respectively. Simulation results of the closed loop systems are presented and discussed in Section 5. In Section 6, comparisons of the proposed controllers with the results obtained from a linearizing PI current controller motivated by the work in [19] are provided. Finally, some concluding remarks are given in Section 7.

2. Model of the SRM including mutual inductances and magnetic saturation effects

Since mutual inductances between two adjacent phases and the magnetic saturation of the iron core have important effects on the performances of the SRM drive and on the torque ripples, a reliable mathematical model which includes these effects has to be adopted to properly evaluate the SRM performances when different control techniques are used. Both spatial and magnetic nonlinearities are inherent characteristics of the SRM; as a result the motor parameters are functions of the rotor position and the phase currents. However, in many linear drive applications, for example [20,21], the SRM is operating in the magnetically linear region where the parameters of the system are expressed as functions of the rotor position only. Bae [19] developed a model which takes into account mutual inductances and the magnetic saturation effects. In this paper, magnetic saturation is considered and the analysis of the SRM is performed assuming that the motor operates in either the linear or the nonlinear magnetic regions. To include the effects of operating in the nonlinear magnetic operating region, the parameters of the system are expressed in terms of both the rotor position and the phase currents.

2.1. The parameters of the SRM

In this paper, we adopt the SRM model developed by Bae [19]. The SRM parameters, such as self and mutual inductances for different rotor positions and phase currents, are obtained analytically by using the finite element method. The SRM parameters are experimentally verified in [19]. In Ref. [22], the SRM parameters were obtained when the phase currents are equal to 1.2 A, while assuming that the motor operates in the linear magnetic region. If the phase currents exceed 1.2 A, the magnetic circuit of the prototype SRM becomes saturated when the rotor moves towards the aligned position. Therefore, the inductances are no longer determined only by the rotor position. Thus, the general form of the inductances at any operating condition with respect to the rotor position and phase currents are represented as follows:

$$\begin{aligned} L_x &= L_x(i_x, \theta) \\ L_y &= L_y(i_y, \theta) \\ M_{xy} &= M_{xy}(i_x, i_y, \theta) \end{aligned} \tag{1}$$