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Average Torque Control of a Switched Reluctance Motor Drive for Light Electric Vehicle Applications ⋆

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Abstract: In this paper, an online average torque control (ATC) of a switched reluctance motor (SRM) for light electric vehicle (LEV) applications is proposed. The purpose of the ATC is to control the average torque in the most inner control loop to stabilize the system dynamics. This is carried out by estimating the average torque at every time instant by considering the motor primary parameters, i.e., rotor position, speed, and phase currents. To achieve the desired average torque in wide speed range and controller efficiency for traction control, the proposed ATC algorithm is designed to adjust the changing reference current and switching angles to obtain the desired average torque at the operating speed. This paper also proposes a torque estimation method based on the Fourier Series approximation of the inductance profile to obtain accurate torque estimation results. The simulation of a 3 kW, 6/4 SRM for LEV application is used to demonstrate the effectiveness of the proposed method.

Keywords: average torque control, switched reluctance motor, light electric vehicle

1. INTRODUCTION

As vehicle production has been continuously increasing all over the globe, the conspicuous problems brought by vehicles have become a great concern these days. Thus, many countries all over the globe, such as China, Japan, etc., have started research on zero emission electric vehicles (EVs). The benefits of EVs are energy saving, environmental friendliness, safe driving, low maintenance, and low noise pollution (Wang Yan, 2011). Moreover, in the present EVs, several types of motors are being used, such as, DC motors, induction motor, permanent magnet motor, and switched reluctance motors. The key advantage of the switched reluctance motor (SRM) is that, it has a simple mechanical construction, i.e., a purely laminated steel structure exists without theany rotor windings, permanent magnets, or squirrel cage bars. Hence, robustness in operation, and high reliability exists in a SRM (D. A. Torrey, 2015; Shahakar, 2013).

The torque control of a SRM does not depend upon the reference model control theory, e.g., field oriented control. However, the torque control is attained by adjusting all control variables according to precalculated or measured functions (J. Zhang, 2015). In indirect instantaneous torque control (IITC), the torque of a SRM is a cascade function, controlled by regulating the instantaneous phase currents (K. Sahoo, 2005). In direct instantaneous torque control (DITC), a digital hysteresis torque controller is designed to obtain a high bandwidth for the drive. However, the torque is estimated by using the terminal quantities, i.e., phase voltages and currents (R. Inderka, 2003a). Various control methods have been proposed in the last few decades to control and estimate torque, and also to minimize the torque ripples of SRMs, (D. A. Torrey, 2015); Sezen, 2016; C. Salame, 2015; Salem, 2014; R. In-derka, 2003b). In hybrid combination of direct torque control (DTC)-sliding mode control (SMC), the torque is estimated by taking in to account the phase flux and phase current. The performance of the adaptive torque controller is also analyzed by considering the mismatch disturbance and parameter uncertainties (Salem, 2014). In high dynamics DTC for SRM, the reference torque is controlled by using the energy ratio estimation technique and also by changing the switching angles (R. Inderka, 2003b). Feedback linearization direct torque control (FL-DTC) based on space vector modulation is used to control the torque and also to reduce the torque and stator flux

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ripples (Y. Choi, 2016). The iterative learning control method is used to control and estimate torque of a SRM by combing the P-type feedback controller with an iterative learning controller (ILC) (K. Sahoo, 2005). However, DTC-sliding mode control, feedback linearization DTC, and sliding mode control based estimation of SRM by using ILC, and IITC based field oriented schemes are all model base techniques. The exact dynamics of the motor need to be known to control and estimate the torque of SRM. Moreover, in these techniques torque is estimated by considering the primary and secondary parameters of a motor, i.e., terminal phase currents, voltages, and flux linkages. Furthermore, the literature discussed above reveals that the torque is also estimated by using the Fourier series (FS) of the inductance profile up to the 3rd or more harmonics. Hence, this increases the system complexity (C. Moron, 2012).

To overcome these issues, an average torque control (ATC) of a SRM drive for LEVs is proposed. The linear estimated torque of a SRM for LEVs is obtained by accumulating the torque of each phase, and a linear magnetic model of a SRM is established to estimate an average torque. The estimated inductance and flux-linkage of a SRM with their FS is considered only for first harmonics. Consequently, in order to control the average torque in SRM traction, control/drive control is used. The purpose of this classical control is to adjust all control variables of a drive at every operating point, i.e., reference current, turning on and turning off the switching angles. These control variables are being set for the entire operating range according to the predetermined lookup tables. These lookup tables play an important role for properly selecting the control variables for each operating point and also depend upon the reference torque, and the speed of the motor for LEV applications. Hence, the key advantages of the proposed control are: **a)** it has the highest degree of flexibility and control level **b)** it provides the minimum speed to hight speed operational area **c)** it provides fast torque control.

2. DYNAMICS AND MODELING DESCRIPTION OF A SRM DRIVE

2.1 Mathematical Preliminaries of a SRM

The overall dynamics of a SRM consist of a set of electrical equations of every phase and the mechanical equation of the system (L. Kalaivani, 2013; Miller, 2001). The phase voltage equation of a SRM is expressed as:

$$V = Ri + \frac{d\lambda(\theta, i)}{dt} \tag{1}$$

where, $\lambda(\theta, i)$ is the phase flux linkage nonlinear function of rotor position (θ), and the phase current (i) using a magnetically linear approximation, where, $\lambda(\theta, i) = L(\theta, i)\, i$. L is the inductance. The flux linkage non-linear function is expressed as:

$$V = Ri + L(\theta, i)\frac{di}{dt} + \frac{dL(\theta, i)}{d\theta} i\,\omega \tag{2}$$

The graphical interpretation of differential stored energy and differential co-energy is expressed in Fig. 1 by taking into account the nonlinear magnetization saturation. The energy equation for a SRM torque production is generally expressed as:

$$dE_{\mathrm{e}} = dE_{\mathrm{f}} + dE_{\mathrm{m}} \tag{3}$$

where, $dE_{\mathrm{e}} = \alpha\, i\, dt$, and $\alpha = V - R\,i$. dE_{e} is called differential electrical energy. dE_{f}, dE_{m} are differential stored field energy (magnetic energy) and mechanical energy (co-energy), respectively. The differential stored field energy is divided into its constituent component as (A. Cheok, 2002):

$$dE_{\mathrm{f}} = \frac{\partial E_{\mathrm{f}}}{\partial i} di\,|_{\theta=\mathrm{constant}} + \frac{\partial E_{\mathrm{f}}}{\partial \theta} d\theta\,|_{i=\mathrm{constant}} \tag{4}$$

By considering the stored differential field energy as (Miller, 2001):

$$dE_{\mathrm{e}} = i\frac{\partial \lambda(\theta, i)}{\partial i} di\,|_{\theta=\mathrm{constant}} + i\frac{\partial \lambda(\theta, i)}{\partial \theta} d\theta\,|_{i=\mathrm{constant}} \tag{5}$$

By substituting (4) into (5) yields,

$$dE_{\mathrm{m}} = i\frac{\partial \lambda(\theta, i)}{\partial \theta} d\theta - \frac{\partial E_{\mathrm{f}}}{\partial \theta} d\theta \tag{6}$$

The overall instantaneous torque is defined as:

$$T_{\mathrm{e}}(\theta, i) = \frac{dE_{\mathrm{m}}}{d\theta} \tag{7}$$

By substituting (6) into (7) returns,

$$T_{\mathrm{e}}(\theta, i) = i\frac{\partial \lambda(\theta, i)}{\partial \theta} - \frac{\partial E_{\mathrm{f}}}{\partial \theta} \tag{8}$$

Note that, the equation (8) is rarely used, and it is called variant of the conventional torque equation. However, it is normally written as a function of co-energy form which is used in this paper to compute torque of a SRM and it is expressed as:

$$T_{\mathrm{e}}(\theta, i) = \frac{\partial E_{\mathrm{coenergy}}}{\partial \theta}|_{i=\mathrm{constant}} \tag{9}$$

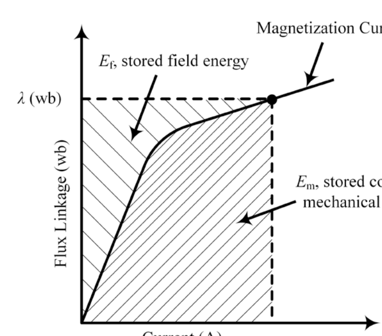

Fig. 1. Graphical interpretation of stored energy and co-energy