전기자동차용 스위치드 릴럭턴스 전동기의 강인 적응형 회생제동제어

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Robust Adaptive Regenerative Braking control of Switched Reluctance Machine for electric vehicles

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Abstract - This paper describes a robust adaptive sliding mode control (RASMC) for torque ripple minimization of switched reluctance motor (SRM) using it in automotive application. The objective is to control effort smoothness while the system is under perturbations by unstructured uncertainties, unknown parameters and external disturbances. The control algorithm employs an adaptive approach to remove the need for prior knowledge within the bound of perturbations. This is suitable for tackling the chattering problem in the sliding motion of sliding mode control method. The algorithm then incorporates modifications in order to build a chattering-free modified robust adaptive sliding mode control using Lyapunov stability theory.

1. Introduction

During the last two decades, various investigations have been devoted to the field of switched reluctance motors (SRMs) due to such advantages as lower costs and higher reliability, over PM-based machines in automotive applications. SRM with an extended speed range at constant power can minimize the power rating of the propulsion system for achieving the same acceleration performance and can also recover more kinetic energy during regenerative braking [1]. Therefore, SRM is becoming increasingly candidate for Electric Vehicles (EVs) application.

However, high torque ripple of SRM overwhelmed these advantages especially for the usage of SRM as a traction motor for fully electrified vehicles with high driving torque that vibration force directly applied on wheels [2]. Therefore advanced methods is needed to reduce the torque ripple of SRM to deliver smoother power to the wheels [3]. This can be achieved by applying smoother control effort even in the presence of disturbance torques to reduce mechanical vibration [4] and enhance the comfort level for the occupants [5].

On the other hand, double saliency structure, inherent magnetic saturation and time variation of parameters form an uncertain nonlinear mathematical model for the machine. Removing some drawbacks of the conventional mechanical structure design, some advanced control methods such as Robust H_∞ strategies [6] and direct torque sharing methods have been developed to achieve a minimized torque ripple performance. However, in review of the published papers for SRM control, mostly explored the torque ripple minimization with known applied braking torque. Furthermore, uncertainty in the braking torque is inevitable in the applications with variable braking torque condition in automotive applications.

To address the above mentioned issues, sliding mode control method is used to achieve faster torque response with acceptable torque ripple for EVs. Higher order and dynamic sliding mode controls have been used to relax the chattering problem [7]. However, in review of the published papers for speed control of SRM, structured uncertainties have not been considered due to difficulties in stability and robustness analysis. Recently, a considerable attention has been paid to construct the combinational techniques to achieve a chattering-free performance.

In general, chattering-free SMC approaches may be classified in to those interacting with switching gain selection and those modifying the sliding function. Combining the SMC and gain adaptation technique has been proposed to develop an adaptive sliding mode control [8]. A modified sliding control designed in, which replaces the discontinuous *sign* function with the appropriate continuous functions to avoid chattering.

Removing the aforementioned drawbacks, this paper proposes an RASMC, as an integrated approach for the chattering-free speed control of an SRM with robust tracking performance. The proposed scheme is capable of rejecting any unknown time-varying perturbations with attenuating the torque ripples. Moreover, the smoothness in the control effort provides a superior performance in braking torque disturbance rejection, compared with the conventional adaptive SMC (CASMC) methods, despite the both electrical and mechanical uncertainties of SRM.

2. Design of robust adaptive speed control

The previous section focused on using an adaptive scheme to estimate the upper bound of uncertainties. However, the linear model of SRM is used and only the mechanical uncertainties is considered.

This section proposes an effective solution for eliminating chattering by introducing the using of RASMC, and incorporating exponential functions. Such modification that is effective in both reducing chattering and smoothing the control effort is developed to overcome the both mechanical and electrical uncertainties in the SRM model and the time-varying braking torque disturbances. The upper bound of perturbations is not required in the design procedure and is estimated by an adaptation mechanism to make the control gain small enough. The current dynamics can be written as:

$$\frac{di_j}{dt}=\left(\frac{d\lambda(\theta,i_j)}{di_j}\right)^{-1}\left(-ri_j-\frac{d\lambda(\theta,i_j)}{d\theta}\omega+v_j\right) \tag{1}$$

where $j=1,2,3,4$ represents the four phases of machine. The SRM dynamic model can be described in an affine form as [7]:

$$\dot{x}_1=x_2,\ \dot{x}_2=f(x,t)+g(x,t)u \tag{2}$$

where, $x=[x_1,x_2]=[\omega,\dot{\omega}]$ and u, respectively represent the state vector and control input. Defining $y=x_1=\omega$ as the output, the dynamic model can be represented in the second-order compact affine form

$$\ddot{y}=f(x,t)+g(x,t)u \tag{3}$$

where the nonlinear functions $f(x,t)$ and $g(x,t)$ are specified by [7]:

$$f(x,t)=\frac{1}{J}\sum_{j=1}^{4}\frac{\left(\dfrac{dT_e(\theta,i_j)}{di_j}\right)}{\left(\dfrac{d\lambda(\theta,i_j)}{di_j}\right)}\left(-ri_j-\frac{d\lambda(\theta,i_j)}{d\theta}\omega\right) \tag{4}$$

$$+\frac{1}{J}\left\{\omega\sum_{j=1}^{4}\left(\frac{dT_e(\theta,i_j)}{d\theta}\right)-B\dot{\omega}\right\}-\frac{T_u(t)}{J}=f_0-\frac{T_u(t)}{J}$$

$$g(x,t)=\frac{1}{J}\left(\frac{dT_e(\theta,i_j)}{di_j}\right)\left(\frac{d\lambda(\theta,i_j)}{di_j}\right)^{-1}$$

in which, $T_u(t)$ denotes the rate of variations in load torque, assumed here as a time-varying disturbance with unknown bound. In (4), the partial derivatives of flux and torque with respect to current and position are calculated by using the electromagnetic characteristics, achieved by the finite element method and verified by experimental measurement.

As a preliminary step to design procedure, rewrite (3) despite the time-varying external disturbance $d(t)$ as

$$\ddot{y} = f(x,t) + g(x,t)u + d(t) \tag{5}$$

The uncertain nonlinear term is decomposed as:

$$f(x,t) = f_0(x,t) + \Delta f(x,t) \tag{6}$$

where $f_0(x,t)$ is the known part and $\Delta f(x,t)$ represents the model uncertainty with unknown bound. By augmenting the unknown uncertainty $\Delta f(x,t)$ and the external disturbance $d(t)$, an unknown time-varying uncertainty is defined as

$$h(x) = \Delta f(x,t) + d(t) \tag{7}$$

Hence, the SRM nonlinear dynamic model (3) takes the form

$$\ddot{y} = f(x,t) + g(x,t)u + h(t) \tag{8}$$

The goal is to design a controller that adaptively tunes the controller gain while all the closed-loop signals are bounded.

Assumption 1. The time-varying augmented parameter $h(t)$ is bounded by the unknown constant $\alpha > 0$, i.e., $\| h(t) \| < \alpha$.
Assumption 2. Without loss of generality, assume $g(x,t) > 0$, to derive the control law. However, this assumption is always satisfied for SRM, as the expressions $\frac{d\lambda(\theta,i_j)}{di_j}$ and $\frac{dT(\theta,i_j)}{di_j}$ are shown to be positive.
Considering $\lambda(\theta,i) = L(\theta,i)i$ one obtains

$$\frac{d\lambda(\theta,i)}{di} = L(\theta,i) + i\frac{dL(\theta,i)}{di} \tag{9}$$

From a physical viewpoint, it is true to assume the positivity of (9) in the range of operation [4], i.e.:

$$L(\theta,i) + i\frac{dL(\theta,i)}{di} > 0 > \epsilon$$

Moreover, consider the fact that the rotor pole arc of the used SRM is larger than its stator pole arc, and the inductance profile does not contain the flatness characteristic. Hence, the coefficient of partial derivative of inductance to position in the produced electromagnetic torque is always positive.

Theorem 1. Consider the SRM uncertain dynamic model (8) with assumptions 1 and 2. For notational consistency, the arguments of $f_0(x,t)$ and $g_0(x,t)$ are omitted during the proof procedures. The reference speed tracking, without any steady state error is ensured by using the control law

$$u = -\frac{1}{g}\left[Ke + \left(\left|f_0 - \dot{\omega}_{ref}\right| + \hat{\alpha}\right)sign(e)\right] \tag{10}$$

where $K > 0$ is the state feedback gain, $e = \omega_{ref} - \omega$ denotes the error, and $\hat{\alpha}$ is an estimation of α, updated by the adaptation mechanism

$$\dot{\hat{\alpha}} = \gamma|e|,\ \hat{\alpha}(0) = 0 \tag{11}$$

in which $\gamma > 0$ is the adaptation gain.
Proof. Consider the Lyapunov function

$$V = \frac{1}{2}e^2 + \frac{1}{2}\frac{1}{\gamma}\tilde{\alpha}^2 \tag{12}$$

where $\tilde{\alpha} = \alpha - \hat{\alpha}$ denotes the estimation error. The time derivative of V is $\dot{V} = e\dot{e} + \frac{1}{\gamma}\tilde{\alpha}\dot{\hat{\alpha}}$. Substituting the error dynamics

$$\dot{e} = \dot{\omega} - \dot{\omega}_{ref} = f_0 - \dot{\omega}_{ref} + \alpha(t) + gu(t) \tag{13}$$

in Lyapunov function, one obtains

$$\dot{V} = \left(f_0 - \dot{\omega}_{ref}\right)e + \alpha(t)e + gu(t)e - \frac{1}{\gamma}\tilde{\alpha}\dot{\hat{\alpha}} \tag{14}$$

By assumption 1, $\dot{V}$ is bounded as

$$\dot{V} \le \left|\left(f_0 - \dot{\omega}_{ref}\right)e\right| + \alpha|e| + gu(t)e - \frac{1}{\gamma}\tilde{\alpha}\dot{\hat{\alpha}} \tag{15}$$

Incorporating control law (11) into (15) yields

$$\begin{aligned}\dot{V} \le & \left|\left(f_0 - \dot{\omega}_{ref}\right)e\right| + \alpha|e| - Ke^2 \\ & - \left|\left(f_0 - \dot{\omega}_{ref}\right)\right||e| - \hat{\alpha}|e| - \frac{1}{\gamma}\tilde{\alpha}\dot{\hat{\alpha}}\end{aligned} \tag{16}$$

Finally, replacing the adaptive law in (15) gives

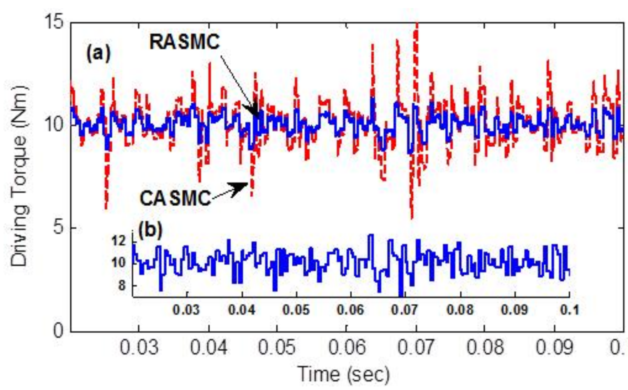
$$\dot{V} \le -Ke^2$$

by which the convergence of the tracking error to zero at finite time can be concluded.

2.3 Simulation Results

Simulation results are presented for a 4 kW SRM. the controller parameters are selected by trial and error.. Moreover, the turn on and turn off angles is assumed to be constant and equal to 33^o and 56^o, respectively.
The load torque, applied to the motor, is perturbed by a Gaussian noise with a mean torque value of 10 Nm and a variance of 1 Nm. This kind of load torque perturbations is selected to emulate the electric vehicle driving torque condition [9]. As plotted in Fig. 1, only a small ripple remains in the steady state by applying the RASMC.

The chattering in control effort is completely removed by the RASMC, as depicted in Figs 2(a) and (b).



<Fig. 1> Torque estimation in the presence of a Gaussian perturbation with a mean of 10 Nm and variance of 1, (a) time history,(b) load perturbation.

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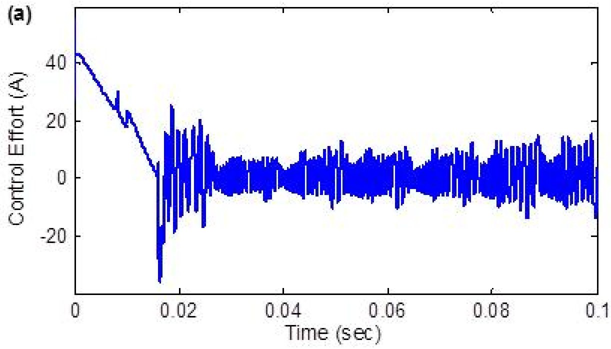

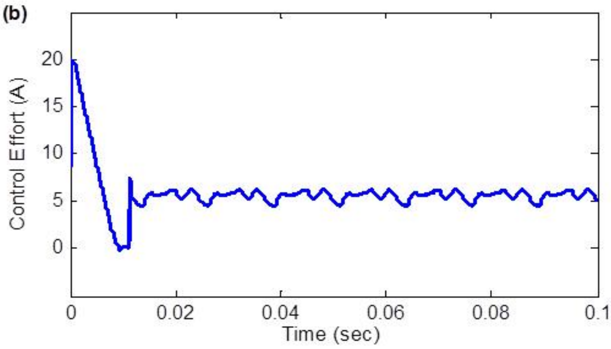

<Fig. 2> Control efforts in simulation (a) CASMC, (b) RASMC

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