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H_∞ Control Applied to Electric Torque Control for Regenerative Braking of an Electric Vehicle

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Abstract: The state space model and the design of H_∞ robust controller for regenerative braking of an EV(electric vehicle) driven by permanent magnet DC motor were presented. The controller was developed to make a good combination between regenerative braking and mechanical friction braking system and to minimize the effect of disturbance, such as the variation of initial speed and driving mode. The experimental results with different initial speed and driving modes show that energy saving and good combination between regenerative braking and mechanical friction braking are synchronously available by H_∞ controller and the H_∞ controller is prior to the traditional PID controller in both steady-state tracking error and response speed.

Key words: Electric vehicle, regenerative braking, electric braking torque, H_∞ control

INTRODUCTION

Regenerative braking allows the EV to use the motor as a generator when the brakes were applied, to pump the kinetic energy from the braking system into battery or other kinds of energy storage devices, such as ultracapacitor. Regenerative braking is an effective approach to extend the driving range of EV and can save from 8% to as much as 25% of the total energy used by the vehicle, depending on the driving cycle and how it was driven[1]. Several driving systems with regenerative braking facility have been reported in the past few years[2,3]. Obviously, a mechanical friction braking system must be attached to regenerative braking system which cannot handle large braking power at the situation of hard braking at high speed.

To making a good combination between regenerative braking and mechanical friction braking system, the electric braking torque should be in proportion to the pressure applied to the brake pedal. In this paper, a regenerative braking control system is proposed which regulate the armature current of the traction motor to make a good combination between regenerative braking and mechanical friction braking system.

During braking, the back EMF (Electromotive Force) of the motor will greatly reduced, for example, from more than one hundred volt to tens of volt within several seconds. The tasks of the controller are to stabilize the system and to minimize the error between electric braking torque and its reference value given by braking pedal, in spite of the large perturbations in the back EMF of traction motor in all kinds of driving cycle.

H_∞ control theory has been used in practical design problems since the early 1980s and has been used more recently as a design tool in the area of power electronics and especially in DC/DC converters due to the fact that the derived controller can also be used in large signal applications[4-6]. The suboptimal solution of the standard problem can be found via the description of the linearized system in state space and the solution of two algebraic Riccati equations.

This study attempt to design a controller based on H_∞ robust control theory and MATLAB and to make a good combination between regenerative braking and mechanical friction braking system under the presence of disturbance, such as the variation of initial speed and driving mode. Furthermore, experimental results are provided in this study.

MATERIALS AND METHODS

Circuit topology of the experimental vehicle: Figure 1 shows the circuit topology of XJTUEV-1, which is an electrical microbus reconstructed by the Center for Research and Development of Electric Vehicle of Xi'an Jiaotong University. The vehicle was driven by a 20 kW permanent magnet DC motor and has a total weight of 1400 kg and maximum speed of 60 km h^{-1} and the switching frequency of transistor is 20 kHz.

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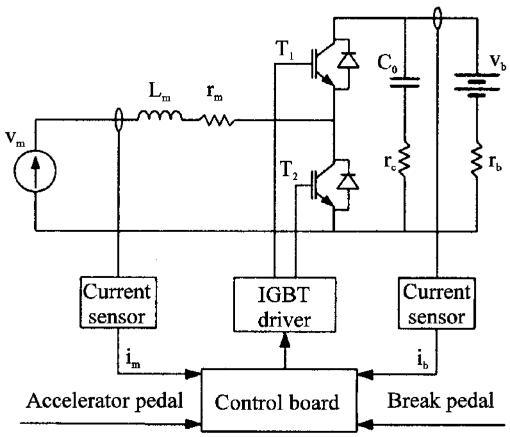


Fig. 1: Circuit topology of XJTUEV-1

In the Fig. 1, v_b denotes the voltage of battery pack, C_0 is capacitor, T_1 and T_2 are IGBT (Isolated Gate Bipolar Transistor), i_b and i_m are respectively, battery and armature winding current. L_m and r_m are respectively, armature winding inductance and resistance, v_m denotes the back EMF of armature winding. r_b and r_c are ESR (Equivalent Series Resistance).

State space model of regenerative braking: During regenerative braking, T_2 works on PWM (Pulse Width Modulation) mode, T_1 shuts off all the time and the current flows in the same way as in a standard Boost DC/DC converter[7] and the electric energy converted from kinetic energy is pumped to the battery. The equations for two circuit configurations of regenerative braking corresponding to the two states of transistor T_2 expressed in standard state space form are:

Interval 1, T_2 switch ON, $0 \le t \le dT$

$$\begin{cases} \dfrac{di_m}{dt} = -\dfrac{r_m}{L} i_m + \dfrac{1}{L} v_m \\ \dfrac{dv_c}{dt} = -\dfrac{v_c - v_b}{(r_b + r_c)\,C} \end{cases} \tag{1}$$

Interval 2, T_2 switch OFF, $dT \le t \le T$

$$\begin{cases} \dfrac{di_m}{dt} = -\dfrac{1}{L}\left(r_m + \dfrac{r_b r_c}{r_b + r_c}\right) i_m - \dfrac{r_b v_c + r_c v_b}{L(r_b + r_c)} + \dfrac{1}{L} v_m \\ \dfrac{dv_c}{dt} = \dfrac{r_b}{(r_b + r_c)C} i_m - \dfrac{v_c - v_b}{(r_b + r_c)C} \end{cases} \tag{2}$$

Where, d is the duty cycle and T is the operation period of transistor T_2. After the well-known averaging and perturbation processing[8], the linearized model of power stage of regenerative braking is described as:

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ \tilde{i}_m &= Cx + D_{21} w + D_{22} u \end{aligned} \tag{3}$$

The state-space variable x contains $\tilde{i}_m$ and $\tilde{v}_C$ the control input u is the duty cycle variation, the symbol of ~ denotes the variation of variable from its nominal value.

Design of H_∞ controller: A general plant G(s) is described by equations of the form:

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{21} w + D_{22} u \end{aligned} \tag{4}$$

The design of the controller for this problem can be translated to the standard problem of H_∞ control as given in Fig. 2.

In the diagram, P_0 is the power stage of regenerative braking, as given in Eq. 3. G'(s) is the augmented plant for P_0, K(s) is the controller to be designed. Weighting function W_m and W_b represent perturbations in the back EMF of motor and terminal voltage of battery from their nominal values. We weights the difference between the response of the plant and the reference value and limits the maximum value of the error caused by perturbation. W_u is used to shape the penalty on control signal[4].

For the standard problem of H_∞ control, four assumptions are made about the plant G(s)[9], but this design example do not satisfy the second assumption, because $D_{21} = [0\ 0]$. In this case, a virtual disturbance signal v is introduced[10], as shown in Fig. 3, to satisfy the assumption and the new augmented plant G(s) is described by a new equation of the form:

$$\begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} A & B_1 & 0 & B_2 \\ C_1 & D_{11} & 0 & D_{12} \\ C_2 & D_{21} & \varepsilon & D_{22} \end{bmatrix} \cdot \begin{bmatrix} w \\ v \\ u \end{bmatrix} \tag{5}$$

If ε is small enough, we can neglect the influence of the introduced disturbance signal v on original system and in this design example, we selected ε as 0.001.

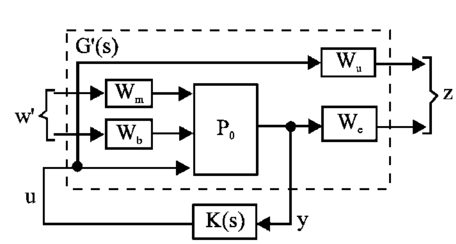


Fig. 2: Standard problem of H_∞ control

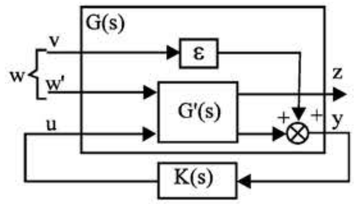


Fig. 3: The introducing of virtual disturbance

The closed-loop transfer function matrix between w and z is defined as T_{zw}. The design goal is to minimize the infinite norm of T_{zw}. By try and error, the four weighting functions in this study are selected as:

$$W_m = 15 \quad W_b = 5 \quad W_e = \frac{s + 200}{0.01s + 100}$$

$$W_u = \frac{5 \cdot 10^4 (s + 1.2 \cdot 10^3)}{s + 3 \cdot 10^8}$$

Using the function sysic and hinfsyn of MATLAB to compute the H_∞ controller

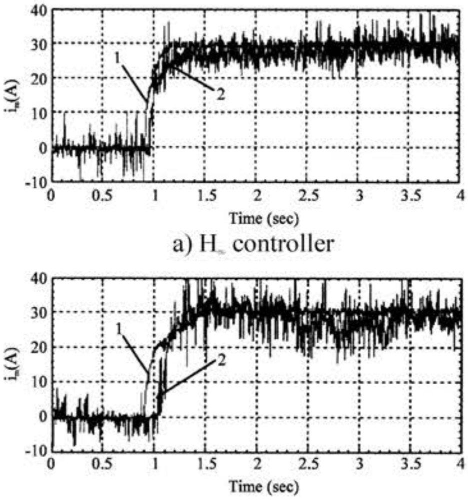
$$K(s) = \frac{4115s^3 + 8.856.10^{11}s^2 + 6.88.10^{17}s + 3.73.10^{20}}{s^4 + 5.96.10s^3 + 1.12.10^{13}s^2 + 6.62.10^{18}s + 4.82.10^{21}} \quad (6)$$

RESULTS

The performance of H_∞ controller described above was evaluated on XJTUEV-1. Figure 4 shows XJTUEV-1 and its controller, which realize two main functions: driving control and regenerative braking control.

To make a good combination between regenerative braking and mechanical friction braking system, the reference value of i_m is set directly by the brake pedal and proportional to the pressure of the brake pedal to coordinate the regenerative braking and mechanicalfriction braking systems and reaches its maximum value of about 53A at half of the full range of the pedal to limit the charging current of the battery.

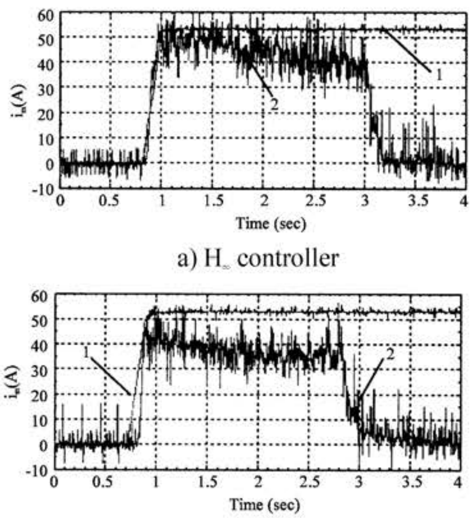
Fig. 4: XTUEV-1 which features regenerative braking



a) H_∞ controller

b) PID controller

Fig. 5: Soft braking at initial speed about 60 km h^{-1}



a) H_∞ controller

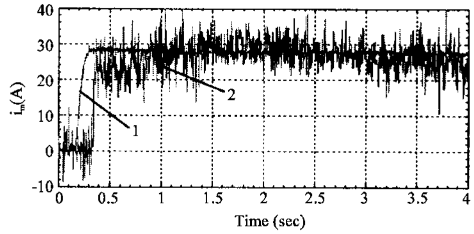
b) PID controller

Fig. 6: Hard braking at initial speed about 60 km h^{-1}

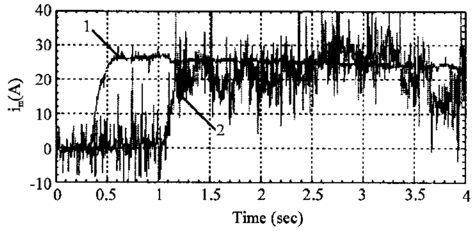
Figure 5-8 show the reference and actual value of i_m when the vehicle braking at different initial speed, with the H_∞ controller and traditional PID controller. In the situation of soft braking, the brake pedal is pressed slightly, the reference value is about 30A, the vehicle requires a long time before a complete stop. In case of hard braking, the brake pedal is pressed deeply and the reference value reaches its maximum value. In Fig. 5-8, wave 1 denotes the reference value of i_m set by braking pedal and 2 is the actual value.

DISCUSSION

Figure 5 and 7 show the situation when the vehicle braking softly at initial speed of 60 and 25 km h^{-1},

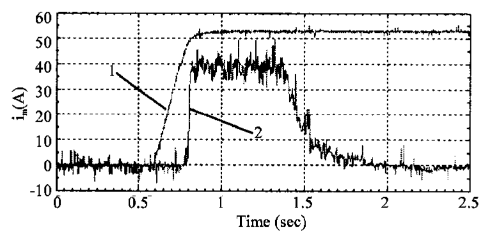


a) H_∞ controller

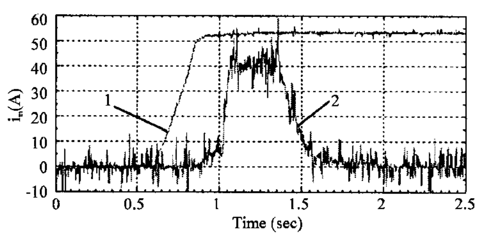


b) PID controller

Fig. 7: Soft braking at initial speed about 25 km h^{-1}



a) H_∞ controller



b) PID controller

Fig. 8: Hard braking at initial speed about 25 km h^{-1}

respectively. Figure 5 indicate that the armature winding current of H_∞ controller is smoother than that of PID controller and on the case of braking at initial speed of 25 km h^{-1}. Figure 7 shows serious delay and oscillation in the armature winding current of PID controller. The experimental results shown in Fig. 5 and 7 showed that the fact that more sensitive and smooth braking can be implemented by H_∞ controller.

In case of hard braking, as shown in Fig. 6 and 8, the brake pedal is pressed deeply and the vehicle require a short time before a complete stop, for example, about 2.5 sec is required when the initial speed is 60 km h^{-1}, about 1 sec is required when the initial speed is 25 km h^{-1}. While hard braking, the huge braking torque provided by mechanical braking system can be regard as serious disturbance for regenerative braking controller, it can be seen from Fig. 6 and 8 that the H_∞ controller is more robust than PID controller. For example, the average current is 45 and 35 A with H_∞ controller and PID controller respectively, as shown in Fig. 6. Furthermore, the PID controller has large delay than H_∞ controller as shown in Fig. 8. From the viewpoint of energy saving, Fig. 6 and 8 showed that the fact that more energy can be saved by H_∞ controller because it has smaller delay and steady state error than PID controller.

The experimental results under different driving modes shown in Fig. 5 to 8 provide a comparison between the H_∞ robust controller and traditional PID controller and prove that the performance of the H_∞ robust controller is prior to that of the PID controller in both the steady-state tracking error and response speed in spite of the variations in back EMF of traction motor and the initial speed of the vehicle.

The traditional PID control is an effective approach for most of the industry applications, but for regenerative braking of electric vehicle, because of the large variation of initial speed and driving mode, H_∞ robust control theory become an effective approach for this application. In summary, energy saving and good combination between regenerative braking and mechanical friction braking can be synchronously available by using H_∞ controller.

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