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

Zhi-Feng Bai, Shu-Xin Li and Bing-Gang Cao
Department of Mechatronics Engineering, Xi’an Jiaotong University,
No. 28, Xianning West Road, Xi’an, Shaanxi Province, People’s Republic of China, 710049

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[9]. Several driving systems with regenerative braking facility have been reported in the past few years[10,11]. 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 make 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[12,13]. 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 XJUVEV-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.

Corresponding Author: Zhi-Feng Bai, Department of Mechatronics Engineering, Xi’an Jiaotong University, No. 28, Xianning West Road, Xi’an, Shaanxi Province, People’s Republic of China, 710049
Tel: 86 29 82668835 Fax: 86 29 82665331 E-mail: ev_center@mail.xjtu.edu.cn

1103
In the Fig. 1, $v_b$ denotes the voltage of battery pack, $C_i$ is capacitor, $T_1$ and $T_2$ are IGBT (Isolated Gate Bipolar Transistor), $i_a$ and $i_w$ are respectively, battery and armature winding current. $L_n$ and $r_n$ are respectively, armature winding inductance and resistance, $v_n$ denotes the back EMF of armature winding. $r_b$ and $r_s$ 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 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:

\[
\frac{di_a}{dt} = \frac{r_n}{L_n} i_a + \frac{1}{L} v_n
\]

\[
\frac{dv_n}{dt} = \frac{v_n - V_0}{(r_b + r_s)C}
\]

**Interval 2, $T_2$ switch OFF, $dt \leq t \leq T$$}$

\[
\frac{di_a}{dt} = \frac{r_n}{L_n} (i_a + \frac{r_s}{r_b + r_s})i_a + \frac{r_s v_n + v_a}{L(r_b + r_s)} + \frac{1}{L} v_n
\]

\[
\frac{dv_a}{dt} = \frac{r_s}{(r_b + r_s)C} i_a - \frac{v_a - v_n}{(r_b + r_s)C}
\]

Where, $d$ is the duty cycle and $T$ is the operation period of transistor $T_2$. After the well-known averaging and perturbation processing\(^{[5]}\), the linearized model of power stage of regenerative braking is described as:

\[
\dot{x} = A x + B_1 w + B_2 u
\]

\[
\dot{i}_n = C x + D_1 w + D_2 u
\]

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

**Design of $H_\iota$ controller:** A general plant $G(s)$ is described by equations of the form:

\[
\dot{x} = Ax + B_1 w + B_2 u
\]

\[
z = C_1 x + D_1 w + D_2 u
\]

\[
y = C_2 x + D_2 w + D_3 u
\]

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

In the diagram, $P_o$ is the power stage of regenerative braking, as given in Eq. 3. $G(s)$ is the augmented plant for $P_o$, $K(s)$ is the controller to be designed. Weighting function $W_n$ and $W_p$ 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\(^{[1]}\).

For the standard problem of $H_\iota$ control, four assumptions are made about the plant $G(s)$\(^{[3]}\), 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\(^{[8]}\), 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:

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

If $\varepsilon$ is small enough, we can neglect the influence of the introduced disturbance signal $v$ on original system and in this design example, we selected $\varepsilon$ as 0.001.
Fig. 3: The introducing of virtual disturbance

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

\[
W_m = 15 \quad W_h = 5 \quad W_e = \frac{s + 200}{0.01s + 100} \\
W_u = \frac{5 \times 10^4(s + 1.2 \times 10^7)}{s + 3 \times 10^8}
\]

Using the function sysic and hinfsyn of MATLAB to compute the \( H \) controller

\[
K(s) = \frac{4115s^3 + 8.856.10^3s^2 + 6.88.10^3s + 3.73.10^8}{s^4 + 5.96.10^3s^3 + 1.12.10^5s^2 + 6.62.10^5s + 4.82.10^7}
\]

(6)

RESULTS

The performance of \( H \) controller described above was evaluated on XJUEV-1. Figure 4 shows XJUEV-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 \( i_{in} \) is set directly by the brake pedal and proportional to the pressure of the brake pedal to coordinate the regenerative braking and mechanical friction 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

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

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

Figure 5-8 show the reference and actual value of \( i_{in} \) 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 \( i_{in} \) 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\(^{-1}\),
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\(_c\) controller is more robust than PID controller. For example, the average current is 45 and 35 A with H\(_c\) controller and PID controller respectively, as shown in Fig. 6. Furthermore, the PID controller has large delay than H\(_c\) 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\(_c\) 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\(_c\) robust controller and traditional PID controller and prove that the performance of the H\(_c\) 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\(_c\) 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\(_c\) controller.

REFERENCES


