International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 592

PEM FUEL CELL-FED BIDIRECTIONAL DC MOTOR SYSTEM TRACKING CONTROL BY USING ADAPTIVE BACKSTEPPING SLIDING-MODE APPROACH

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ABSTRACT

Proton exchange membrane (PEM) fuel cell, a clean and alternative power source, has become a research hotspot in recent years. In general, PEM fuel cell-fed DC motor can only rotate unidirectionally. In this paper, a full-bridge converter is proposed to form PEM fuel cell-fed bidirectional DC motor system, and an adaptive backstepping sliding-mode control (ABSMC) is proposed to achieve the bidirectional angular velocity tracking and bus voltage regulation. The control-oriented model of the PEM fuel cell-fed motor system is constructed. The control laws and adaptive laws are developed following the sliding-mode controller with backstepping approach to achieve bus voltage and angular velocity regulations. As a comparison, a traditional PI control is used, and the two controllers are compared through simulations. The results indicate that ABSMC show better control performance under the circumstance of system parameters variations and external disturbances no matter in bus voltage or angular velocity regulation. In particular, the PEM fuel cell can be protected via ABSMC since the controller reduced the impact of the load variation.

Keywords: proton exchange membrane (PEM) fuel cell, DC/DC buck converter, DC motor, adaptive backstepping sliding-mode control (ABSMC)

1. INTRODUCTION

Fuel cell, as a highly efficient clean energy, is beneficial to deal with the problem of energy shortage. Among various fuel cells, proton exchange membrane (PEM) fuel cell is preferred due to its higher energy density, lower noise, and faster star-up feature [1]. Thus, in recent years, PEM fuel cell is widely used in vehicles to reduce emissions and improve driving range [2]. In addition, PEM fuel cell can be hybridized with other renewable power systems such as the wind power and solar cells to provide electricity [3]. To meet the DC motor working requirement like stable and desired service voltage, PEM fuel cell is usually adopted by DC/DC converters [4]. Generally, these DC/DC converters can guarantee smooth starter of DC motor, and specifically, DC/DC buck converters reduce the noisy shape due to the hard switching of the PWM.

In practice, time-varying parameters in capacitance and inductance of DC/DC buck converters are unavoidable, and input voltage and load resistance are frequently changed which result in uncertainties as well as disturbances. Ahmad et al. [5] proposed a model predictive control (MPC) for DC/DC buck converters applied in a photovoltaic system. Based on two GPI observers, [6] designed a robust controller for DC/DC buck converters to estimate the lumped time-varying disturbances. The operating voltage of DC motor is regulated by DC/DC buck converter, and for different working conditions, the angular velocity of motor is general different. K. V. R. Swathi *et al*. [7] presented angular velocity controller for DC/DC buck converter–DC motor system, and for a better performance under changes of velocity and torque references. In order to enable the bidirectional rotation, a full bridge converter between DC/DC buck converter and DC motor has been normally used to generate positive and negative current. In particular, the DC/DC buck converter–full bridge converter–DC motor model can control the motor angular velocity and bus voltage simultaneously.

An adaptive backstepping sliding-mode control (ABSMC) combines the advantages of sliding-mode

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

control (SMC) and backstepping SMC. In [8], a novel ABSMC with fuzzy monitoring strategy is proposed to control a kind of nonlinear mechanical system, which can drive system trajectory to set point in finite-time.

This study presents a control-oriented model according to the equivalent-circuit of PEM fuel cell, converters, and motor, and an adaptive backstepping sliding-mode control (ABSMC) to implement motor bidirectional rotating following the reference velocity.

2. PEM FUEL CELL-FED BIDIRECTIONAL DC MOTOR SYSTEM MODELING

The system schematic diagram is shown in Fig 1, consisting of PEM fuel cell, buck converter, full-bridge converter and DC motor. The control-oriented model is composed of a model of PEM fuel cell based on equivalent-circuit method, and an average model of the DC/DC buck converter-bidirectional DC motor system.

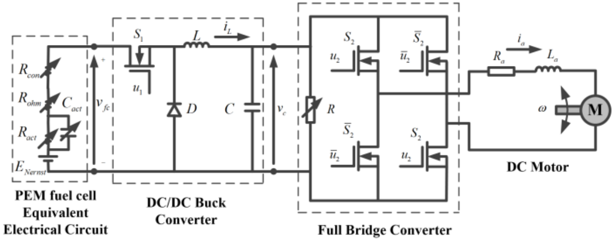

Fig 1 PEM fuel cell-fed bidirectional DC motor system

2.1 PEM Fuel Cell Modeling

PEM fuel cell convert chemical energy into electrical energy through electrochemical reactions. In this paper, the pressure of hydrogen and oxygen is set at 202650 Pa and 101325 Pa respectively. Besides, 333.15 K, a high efficiency operation temperature is used. The output of PEM fuel cell can be described by the varied double-capacitor effect of the equivalent circuit model referring from [1].

2.2 DC/DC Buck Converter-bidirectional DC Motor

The average model of the system is denoted as follows

In practice, there may be uncertainties in system parameters L, C, L_a, and J. Denoting $L=L_0+\Delta L$, $C=C_0+\Delta C$, $L_a= L_{a0}+\Delta L_a$, and $J =J_0+\Delta J$ with known nominal values L_0, C_0 , L_{a0} , and J_0 and bounded uncertain parameters ΔL, ΔC, ΔL_a, and ΔJ. The system can be accurately described by

$$\begin{cases} \dfrac{di_L}{dt} = \left[h\left(u_{1av} i_L\right) u_{1av} - v_c \quad 0 \right] \begin{bmatrix} \dfrac{1}{L_0+\Delta L} \\ \dfrac{1}{C_0+\Delta C} \end{bmatrix} \\ \dfrac{dv_c}{dt} = \left[0 \quad i_L - \dfrac{v_c}{R} - i_a u_{2av} \right] \begin{bmatrix} \dfrac{1}{L_0+\Delta L} \\ \dfrac{1}{C_0+\Delta C} \end{bmatrix} \end{cases} \text{and} \begin{cases} \dfrac{di_a}{dt} = \left[v_c u_{2av} - R_a i_a - k_e \omega \quad 0 \right] \begin{bmatrix} \dfrac{1}{L_{a0}+\Delta L_a} \\ \dfrac{1}{J_0+\Delta J} \end{bmatrix} \\ \dfrac{d\omega}{dt} = \left[0 \quad k_m i_a - B\omega \right] \begin{bmatrix} \dfrac{1}{L_{a0}+\Delta L_a} \\ \dfrac{1}{J_0+\Delta J} \end{bmatrix} \end{cases} \tag{1}$$

where R, L, and C represent the output load, inductance, and capacity of DC/DC buck converter respectively. i_L is the inductor current and v_c is the capacitor output voltage. i_a is the armature current, ω is the angular velocity of DC motor. L_a is the armature inductance, B is viscous friction coefficient, and J is the moment of inertia of the rotor and motor load. k_e is the counterelectromotive force constant, k_m is the motor torque constant. Besides, u_{1av} and u_{2av} represent the system average controls, which ranging from 0 to 1 and -1 to 1 respectively.

The bounded uncertain parameters can be limited by

$$\max\left\{ \left|\Delta L\right|,\ \left|\Delta C\right|,\ \left|\Delta L_a\right|,\ \left|\Delta J\right| \right\} = \left\{ L_m,\ C_m,\ L_{am},\ J_m \right\} \tag{2}$$

3. ADAPTIVE BACKSTEPPING SLIDING-MODE TRACKING CONTROL

3.1 ABSMC Design

The purpose of the control is to track both angular velocity ω and bus voltage v_c to desired values ω_{ref} and $v_{c,ref}$ simultaneously. Moreover, assuming that the desired values are bounded and have n-order bounded derivative. To estimate bounded uncertain parameters ΔL, ΔC, ΔL_a, and ΔJ, the model (1) can be estimated by

$$\begin{cases} \dfrac{di_L}{dt} = \gamma_1^T \hat{\theta} \\ \dfrac{dv_c}{dt} = \gamma_2^T \hat{\theta} \end{cases} \quad \text{and} \quad \begin{cases} \dfrac{di_a}{dt} = \xi_1^T \hat{\vartheta} \\ \dfrac{d\omega}{dt} = \xi_2^T \hat{\vartheta} \end{cases} \tag{3}$$

where $\hat{\theta}$ and $\hat{\vartheta}$ are the estimations of θ and ϑ respectively.

To track output voltage v_c and angular velocity ω, define tracking errors e_1 as bellows

$$e_1 = \left[y_1 \quad z_1 \right]^T = \left[v_c - v_{c,ref} \quad \omega - \omega_{ref} \right]^T \tag{4}$$

Define the second backstepping variable e_2 as

$$e_2 = \begin{bmatrix} y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} \gamma_2^T \theta - \gamma_2^T \tilde{\theta} + a y_1 - \dot{v}_{c,ref} \\ \xi_2^T \vartheta - \xi_2^T \tilde{\vartheta} + b z_1 - \dot{\omega}_{ref} \end{bmatrix} \tag{5}$$

where a and b are positive constants and $\tilde{\theta} = \theta - \hat{\theta}$, the same as $\tilde{\vartheta}$.

Then the sliding manifolds s can be selected as

$$s = \left[s_v \quad s_\omega \right]^T = \left[f y_1 + y_2 \quad g z_1 + z_2 \right] \tag{6}$$

For the stability of the system, define Lyapunov function Ly

$$Ly = \begin{bmatrix} Ly_v \\ Ly_\omega \end{bmatrix} = \begin{bmatrix} \dfrac{1}{2} y_1^2 + \dfrac{1}{2} \tilde{\theta} \Gamma^{-1} \theta + \dfrac{1}{2} s_v^2 \\ \dfrac{1}{2} z_1^2 + \dfrac{1}{2} \tilde{\vartheta} \Gamma^{-1} \vartheta + \dfrac{1}{2} s_\omega^2 \end{bmatrix} \tag{7}$$

where Γ and T are positive define matrix.

To eliminate the estimation error $\tilde{\theta}$ and $\tilde{\vartheta}$ existing in (7), the adaptive laws $\hat{\eta}$ are formulated by

$$\dot{\hat{\eta}} = \begin{bmatrix} \dot{\hat{\theta}} \\ \dot{\hat{\vartheta}} \end{bmatrix} = \begin{bmatrix} s_v \Gamma\left((f+a)\gamma_2 + \frac{1}{\hat{C}}\gamma_1 - \frac{1}{R\hat{C}}\gamma_2 \right) \\ s_\omega \mathrm{T}\left((g+b)\xi_2 + \frac{1}{\hat{J}}k_m\xi_1 - \frac{1}{\hat{J}}B\xi_2 \right) + \mathrm{T}z_1\xi_2 \end{bmatrix} \tag{8}$$

Then the control laws $u = [u_{1av} \quad u_{2av}]^T$ are calculated by

$$\begin{aligned} u_{1av} &= -\frac{\hat{L}\hat{C}}{v_{fc}}\Big\{ -\frac{v_c}{\hat{L}\ddot{C}} + (f+a)\left(\gamma_2^T\hat{\theta} - \dot{v}_{c,ref}\right) - \ddot{v}_{c,ref} + \gamma_2^T\dot{\hat{\theta}} \\ &+ \frac{1}{\hat{C}}\left[-\left(\dot{i}_a u_{2av} + i_a\dot{u}_{av}\right) - \frac{1}{R}\gamma_2^T\hat{\theta} \right] + k[s_v + t\,sign(s_v)] \Big\} \\ u_{2av} &= -\frac{\hat{J}\hat{L}_a}{k_m v_c}\Big\{ -\frac{k_m}{\hat{J}\hat{L}_a}k_e i_a + (g+b)\left(\xi_2^T\hat{\vartheta} - \dot{\omega}_{ref}\right) - \ddot{\omega}_{ref} \\ &+ \xi_2^T\dot{\hat{\vartheta}} - \frac{k_m}{\hat{J}\hat{L}_a}k_e\omega - \frac{1}{\hat{J}}B\xi_2^T\hat{\vartheta} + l\left[s_w + r\,sign(s_\omega)\right] \Big\} \end{aligned} \tag{9}$$

Substituting (8) and (9) into the derivative of (7), $\dot{L}y$ can be obtained by

$$\dot{L}y_v = -\mathrm{Y}^T\mathrm{P}\mathrm{Y} - kt|s_v| - y_1\gamma_2^T\tilde{\theta} \tag{10}$$

Similarly,

$$\dot{L}y_\omega = -\mathrm{Z}^T\mathrm{K}\mathrm{Z} - lr|s_v| - z_1\xi_2^T\tilde{\vartheta} \tag{11}$$

where $\mathrm{Y} = [y_1 \quad y_2']^T = \left[y_1 \quad \gamma_2^T\theta + ay_1 - \dot{v}_{c,ref}\right]^T$

$\mathrm{Z} = [z_1 \quad z_1']^T = \left[z_1 \quad \xi_2^T\vartheta + bz_1 - \dot{\omega}_{ref}\right]$.

If *a*, *b*, *f*, *g*, *l*, and *k* are satisfy as $ak - \frac{1}{4} + fk > 0$ and $bl - \frac{1}{4} + gl > 0$, the matrix P and K are positive define matrix.

Therefore,

$$\dot{L}y_v \le -kt|s_v| - y_1\gamma_2^T\tilde{\theta} \,;\, \dot{L}y_\omega \le -lr|s_\omega| - z_1\xi_2^T\tilde{\vartheta} \tag{12}$$

Based on (2), $y_1\gamma_2^T\tilde{\theta}$ and $z_1\xi_2^T\tilde{\vartheta}$ are bounded by C_m and J_m, and the boundary of them can be defined by

$$-y_1\gamma_2^T\tilde{\theta} \le M \,;\, -z_1\xi_2^T\tilde{\vartheta} \le N \tag{13}$$

To make $\dot{L}y_v, \dot{L}y_\omega \le 0$, *k*, *t*, *l* and *r* should be satisfied as

$$M - kt|s_v| \le 0 \,;\, N - lr|s_\omega| \le 0 \tag{14}$$

The asymptotic convergence of the tracking error can be proved according to the Barbalat's lemma. Define

$$-\dot{L}y(t) \le -\dot{L}y(e_1(t), e_2(t)) \tag{15}$$

Then

$$\int_0^t -\dot{L}y(\tau)dt \le Ly(e_1(0), e_2(0)) - Ly(e_1(t), e_2(t)) \tag{16}$$

yielding,

$$\lim_{t\to\infty}\int_0^t \dot{L}y(\tau)d\tau < \infty \tag{17}$$

Based on Barbalat's lemma, $\dot{L}y(t)$ converges to zero. Hence, proposed ABSMC is asymptotically stable in case of time-varying parameter uncertainties and external disturbances exist.

3.2 Conventional PI Controller Design

To test the superiority of ABSMC, a PI control is designed based on the frequency response analysis. The suitable PI controllers for $G_v(s)$ and $G_\omega(s)$ are designed

$$G_{cv}(s) = 0.35 + \frac{1.5}{s} \,;\, G_{c\omega}(s) = 0.81 + \frac{3.3}{s} \tag{18}$$

3.3 Simulation Comparison

The comparison of PI control and ABSMC under different operation conditions was carried out and the specific operation conditions are shown in Table I.

TABLE I

Operation Conditions

Setpoints	Conditions
v_c=12 V, ω=20 rad/s	Condition 1: transient response
v_c=12 V, ω=20 rad/s	Condition 2: disturbance injection *R*=30 Ω @2~3 s and *R*=5 Ω @(1~2 s)∪(3~5 s)
v_c=12 V, ω=20sin(3π/10t) rad/s	Condition3: bidirectional angular velocity tracking

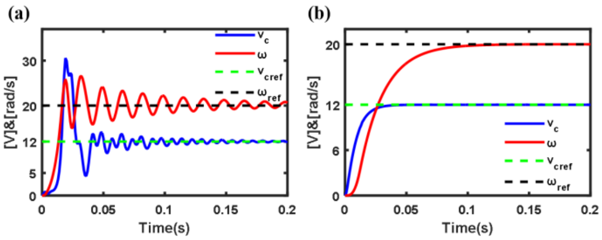

Fig 2 Simulation results of Condition 1: (a) PI control; (b) ABSMC

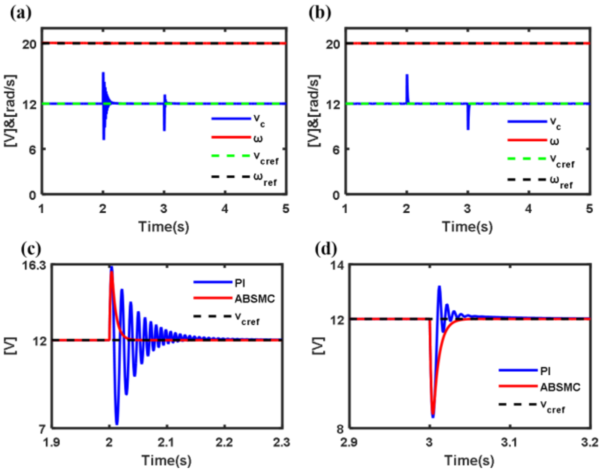

Fig 3 Simulation results of Condition 2: (a) PI control; (b) ABSMC; (c) output voltage controlled by different control methods enlarged view at 2 s; (d) output voltage controlled by different control methods enlarged view at 3 s

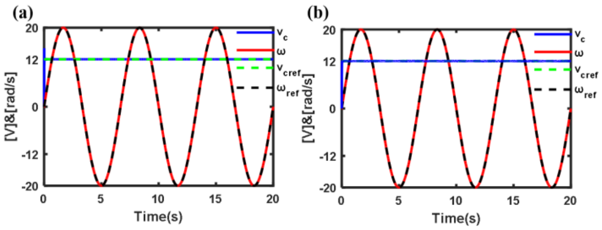

Fig 4 Simulation results of Condition 3: (a) PI control; (b) ABSMC

The simulation results were shown in Fig 2-4. In condition 1, ABSMC showed better performance. The response time of ABSMC was about 0.05 s, less than PI control. Besides, in the process of increasing voltage and angular velocity, ABSMC is smoother than PI control. In terms of disturbance variation simulation results, ABSMC indicated robust performance with fast stabilization, whereas PI control suffered chattering and large undershoot. The settling time of ABSMC is 0.05 s, while 0.3 s for PI control. Moreover, when the external load changed abruptly from 5 Ω to 30 Ω, PI control had undershoot about 41.6%, while ABSMC eliminated it and overshoot of ABSMC and PI control are about 35.8%. ABSMC had no overshoot when load dropped from 30 Ω to 5 Ω, and the undershoot of two methods are about 33.3%. From Fig 4, the proposed two control strategies can realize bidirectional a1ngular velocity tracking according to the desired values. Besides, the settling time are decreased from 0.8 s to 0.1 s when ABSMC applied in this condition.

4. CONCLUSION

In this paper, a full-bridge converter is first proposed to enable PEM fuel cell-fed DC motor bidirectional rotation. The system model is subsequently constructed according to the equivalent-circuit methods. Then, an adaptive backstepping sliding-mode control (ABSMC), has been designed to control the bus voltage and angular velocity of PEM fuel cell-fed bidirectional DC motor subject to parametric uncertainties and external disturbances. The design process was presented in detail and the designed controller could guarantee the convergence and stability of the closed loop system via Lyapunov methods. Through adaptive laws, parameter uncertainties can be obtained. As comparison, traditional PI control is subsequently designed and the simulations by using traditional PI control and proposed ABSMC separately was carried out. The simulation results confirm that proposed system model allows bidirectional DC motor rotation and revealed that ABSMC improves significantly in the transient response of the angular velocity, bus voltage and step angular velocity tracking by producing lower peak overshoot/undershoot and settling time. Meanwhile, ABSMC shows better robustness against the external disturbance.

ACKNOWLEDGEMENT

This work was supported by the National High Technology Research and Development Program of China (Grant No. 2018YFB0105500), the Natural Science Foundation of Fujian Province of China (Grant No. 2017J01690), the China Postdoctoral Science Foundation (Grant No. 2019M650505), and the Qishan Scholar Program in Fuzhou University (Grant No. XRC-1643).

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