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A novel second-order sliding mode control of hybrid fuel cell/super capacitors power system considering the degradation of the fuel cell

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8 Abstract

4

This paper aims to design a novel control strategy of a single converter hybrid 9 power system including a Proton Exchange Membrane Fuel Cell (PEMFC) 10 and super capacitors for electric vehicle applications. The control objective 11 to be addressed in such systems is to smooth the current of PEMFC consider-12 ing the transient power and sinusoidal disturbance from the load. Moreover, 13 in real-time applications, it is required to ensure the operation by taking 14 into account the component constraints and the degradation of PEMFC. To 15 achieve these goals, a robust nonlinear cascaded voltage control loop is de-16 veloped in this paper. For the inner voltage loop, a second order twisting 17 controller with dynamic saturation scheme is adopted to ensure the conver-18 gence of the DC bus voltage to its reference value as well as to attenuate the 19 oscillations on PEMFC current. For the outer voltage loop, a Proportional 20 Integral controller (PI) with anti-windup scheme is utilized to control the 21 super capacitors voltage at its desired value. Furthermore, in order to con-22 sider the degradation of PEMFC in the controlled system, an estimation of 23 the degradation model parameters has been provided by Cubature Kalman 24 filter. Comparative Hardware-in-the-loop (HIL) tests between the proposed 25 control strategy and the traditional two PI controllers strategy for the hybrid 26 power system is performed. The results of HIL tests verified the effectiveness 27 of the proposed nonlinear control strategy. 28

²⁹ Keywords: Hybrid electric vehicle, proton exchange membrane fuel cell

³⁰ degradation, second order twisting controller, super capacitors,

³¹ Hardware-in-the-loop test bench

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32 1. Introduction

In the last few years, with the increasing pressure of energy crisis and 33 environmental protection, fuel cell technologies have received wide atten-34 tion and application from all over the world [1-3]. Among the current fuel 35 cell technologies, the Proton Exchange Membrane Fuel Cell (PEMFC) is re-36 garded as the most hopeful choice for vehicle and portable applications due 37 to the numerous advantages of high energy efficiency, low operating temper-38 ature, no corrosive fluid hazards, and small size [4, 5]. In spite of these good 39 points, there are still some deficiencies caused by the inherent characteristics 40 of PEMFC [6, 7]. One of the main deficiencies of PEMFC is slow dynamic 41 due to the hydrogen delivery system. Thus, when facing a step demand of 42 load or the load with sudden perturbations, PEMFC will occur fuel starva-43 tion phenomena, which will decrease the lifespan of membranes and influence 44 the performance of PEMFC [8]. For these transient loads mentioned above, 45 a fast dynamic auxiliary power source is necessary to be utilized. Compared 46 with battery, super capacitors (SCs) are considered as a better choice as aux-47 iliary source in terms of high power density, good energy effectiveness and 48 high lifespan (superior than one million cycles). Furthermore, SCs are able 49 to work at even low temperature, such as -20 °C [9]. Therefore, SCs are 50 chosen as auxiliary power source while PEMFC is considered as the main 51 power source in this paper. 52

The architectures for hybrid fuel cell/SCs power system can be divided 53 into three categories: parallel, series and cascaded. Due to the benefits of 54 high reliability and low component stresses, parallel architecture is regarded 55 as the most suitable architecture [10, 11]. For parallel architectures of hybrid 56 fuel cell/SCs power system, there are three types of topologies [9, 12]. The 57 first type is fully-active topology, which consists of two DC/DC converters 58 and each converter is linked to a power source. The second type is passive 59 topology, in which no DC/DC converter is adopted. The main advantage of 60 the first type topology is flexible control performance while the disadvantage 61 is higher costs for expenses. For the second type topology, it costs less but 62 it has the lower controllability. Hence, taking into account a promising bal-63 ance between the economy and control performance, the third type topology, 64 namely semi-active topology on the basis of a single converter is utilized in 65 this study. 66

Currently, there are various control strategies for hybrid multi-source 67 power system studied by other researchers, such as proportional integral (PI) 68 controller and passivity-based controller [13, 14]. However, among these pre-69 vious researches on control strategies, the solution of suppressing disturbance 70 for a hybrid fuel cell/SCs power system with only one converter is not con-71 sidered. Moreover, these mentioned control methods have not taken into 72 account the degradation phenomenon of the hybrid power system. When 73 the hybrid system operates, both the PEMFC and the super capacitors will 74 experience degradation in performance. In the long-term operation of the 75 PEMFC, the electrical resistance, exchange current, and limiting current of 76 the PEMFC will change [15]. Compared with PEMFC, the service life for 77 the super capacitors is longer to a large extent. Due to this fact, degradation 78 phenomenon of SCs is ignored in this study [16]. Therefore, the degradation 79 phenomenon of the PEMFC as well as the external disturbance should be 80 taken into account in the design of the control strategy to effectively improve 81 the dynamic response of the hybrid power system. 82

Sliding mode control approach is one of the most efficient methods for 83 controlling systems with parametric uncertainties and external disturbances 84 [17–21]. Among the sliding mode controllers, the twisting controller is the 85 conventional second order sliding mode control that is applied for perturbed 86 systems with relative degree two affected by bounded disturbance [22, 23]. 87 However, this controller provides a discontinuous control signal. In order 88 to obtain a continuous control signal and still have finite time convergence, 89 the idea of relative degree extension can be used [24]. This idea consists in 90 considering the extra equation $\dot{u} = v$, where u is a real control input and v 91 is a virtual higher order sliding mode discontinuous control input. 92

The aim of this paper is to develop a robust control strategy for the 93 hybrid power system with a single converter considering the degradation 94 phenomenon of PEMFC and the external disturbance. This control strat-95 egy should reject the sudden disturbance and decrease the oscillations on 96 fuel cell current, i.e. provide a smooth behavior of the fuel cell current. 97 To that purpose, and inspired by the idea of relative degree extension, our 98 strategy proposes the usage of twisting controller as virtual control input gc to regulate the DC bus voltage to its reference value. Hence, this strategy 100 ensures the finite time convergence of the DC bus voltage to its reference 101 value while compensating the parametric uncertainty and the external dis-102 turbance. Moreover, it provides a continuous control signal which leads to 103 smooth the fuel cell current and increase the lifespan of PEMFC. The main 104

¹⁰⁵ contributions of this work are the following:

1. The degradation estimation of PEMFC is researched by the method of 107 Cubature Kalman Filter (CKF). The CKF accurately estimates the degra-108 dation state and degradation rate for PEMFC. The estimated degradation 109 of PEMFC is applied to the control of the hybrid power system.

2. A robust cascaded voltage control loop is developed on the basis of twisting controller and PI controller for the single converter hybrid power system integrating the degradation of PEMFC. For protection purpose, the constraints of fuel cell and super capacitors are taken into account in the proposed control scheme.

3. The effectiveness of the proposed control strategy is validated by HIL test experiment. Indeed, the HIL test results show that the proposed control method has better performance than the traditional two PI controllers in view of disturbance suppression in the hybrid fuel cell/SCs power system.

The organization of this paper is as follows: In section 2, the description 119 of the hybrid fuel cell/SCs power system based on a single converter is de-120 tailed. In section 3, the degradation model of PEMFC based on the PEMFC 121 degradation experiment is firstly given. Then, the PEMFC degradation esti-122 mation is made by CKF method. In section 4, the proposed control strategy 123 with limitation constraints for this hybrid power system is described. In 124 section 5, the HIL test results are illustrated to validate the effectiveness of 125 the proposed control strategy. Finally, in section 6, the main conclusions are 126 presented. 127

¹²⁸ 2. Hybrid fuel cell/SCs power system

2.1. Configuration of hybrid fuel cell/SCs power system

The topology of the hybrid fuel cell/SCs power system is presented in Fig.1. The configuration characteristic is a parallel architecture on the basis of a single DC/DC converter, which has taken into account the balance between the economy and control performance compared with other configurations.

As shown in Fig.1, in this hybrid power system, the fuel cell system which provides the main power is linked to the DC bus directly and the SCs pack which supplies the transient power is linked to the DC bus by a bidirectional DC/DC converter.



Figure 1: Hybrid system topology

139 2.2. Model of PEMFC

PEMFC is a kind of fuel cell that uses hydrogen fuel to react with air to generate electricity and heat. PEMFC is mainly developed for transport applications [25]. Usually, a PEMFC stack is composed of multiple cells. Each cell includes proton exchange membrane, electrode, catalyst, gas diffusion layer, and bipolar plate [26].

The output characteristics of PEMFC can usually be represented by the 145 polarization curve, as shown in Fig.2, according to [27]. When the output 146 current is small, the output voltage of PEMFC is mainly affected by the 147 activation polarization [28]. The speed of the activation reaction can be 148 expressed by the exchange current of PEMFC. With the increase of the ex-149 change current, the electrode surface reaction will be more and more active 150 and the activation over potential will grow smaller. When the output current 151 is large, the output voltage of PEMFC is mainly affected by concentration 152 polarization. The loss of voltage is mainly determined by the concentration 153 of reactants and products [29]. The limiting current of PEMFC is usually 154 used to indicate the intensity of the concentration polarization. The larger 155 the limiting current is, the smaller the loss of voltage will be. Ohmic polar-156 ization is caused by the resistance of electrons through the electrode material 157 and the connecting parts, and the protons pass through the membrane. The 158 electrical resistance is usually adopted to indicate the intensity of the con-159 centration polarization. Therefore, the output voltage of PEMFC can be 160 expressed as (1) [15]. 161

$$V_{fc} = E_r - ATln(\frac{i_{fc}}{i_o}) - i_{fc}R_{fc} - BTln(\frac{i_{lim}}{i_{lim} - i_{fc}}),$$
(1)

where V_{fc} is the output voltage of PEMFC, i_{fc} is the current of PEMFC, E_r is the theoretical potential of PEMFC, i_o is the exchange current of PEMFC, i_{lim} is the limiting current of PEMFC, R_{fc} is the electrical resistance of PEMFC, A is the Tafel slope, B is the mass transfer constant, and T is the operating temperature of PEMFC.



Figure 2: The polarization curve of PEMFC

167 2.3. Model of super capacitors

The SCs pack as a voltage source type electrical energy storage element has the advantages of high power density, long lifespan, short charging and discharging time, high reliability and so on. There are a variety of models for developing SCs pack in the existing literature [30]. In this paper, SCs pack is modeled by a voltage source connected to a pure inductor.

173 3. PEMFC degradation

174 3.1. PEMFC degradation experiment

The PEMFC degradation experiment is performed in the FCLAB [27], as shown in Fig.3. The membrane adopts Nafion membrane, and the electrode adopts the platinum nanoparticle catalyst. The PEMFC is operated under constant load current for 1000 h. The PEMFC operating conditions are shown in Table 1.



Figure 3: The PEMFC degradation testing platform

Parameter	Value
Number for cells	5
Active area	100 cm^2
Membrane thickness	$25~\mu{ m m}$
Platinum catalyst	0.2 mg/cm^2
GDL thickness	$415~\mu{\rm m}$
Load current	70 A
Hydrogen pressure	1.3 bar
Temperature	$54 ^{\circ}\mathrm{C}$
Relative humidity	52%

Table 1: The operating parameters of PEMFC

180 3.2. PEMFC degradation model

According to the literatures [31–33], resistance and limiting current vary greatly during the PEMFC degradation. The relationship between resistance and limiting current over time can be expressed as the following equations.

$$R_{fc}(t) = R_{fc}(0)(1 + \alpha(t)), \qquad (2)$$

$$i_{lim}(t) = i_{lim}(0)(1 - \alpha(t)),$$
(3)

184

$$\alpha(t) = \beta t,\tag{4}$$

where α represents the state of health (the indicator of degradation of PEMFC), and β represents the speed of degradation.

187 3.3. Degradation estimation based on Cubature Kalman Filter

¹⁸⁸ The nonlinear system is represented by the following equations.

$$x_{k+1} = f(x_k, u_k) + w_k,$$
(5)

$$y_{k+1} = h(x_{k+1}, u_k) + v_k, (6)$$

where $x = [\alpha; \beta]$ is the system state, $y = [V_{fc}]$ is the output state of system, 189 u_k is the input of system, f is the state transfer function from x_k to x_{k+1} , h 190 represents the system measurement function, w_k and v_k represent the system 191 process noise and system measurement noise respectively. The w_k and v_k are 192 considered as the Gaussian noises with zero mean and covariance Q and R. 193 The CKF based on the spherical-radial cubature rule produces a set of 194 cubature points to estimate the state of a nonlinear system [34, 35]. Since the 195 cubature rule does not require derivatives, the CKF has less computational 196 effort [36]. Compared with conventional nonlinear filters, CKF has higher 197 filtering accuracy [34]. The basic process of CKF state estimation is shown 198 below: 199

1). Initialization: initialize state and covariance

$$\hat{x}_0 = E[x_0], P_0 = Var[x_0].$$
 (7)

201 2). Calculate cubature points

$$P_k = S_k S_k^T, \tag{8}$$

202

$$x_k^i = S_k \gamma_i + \hat{x}_k, \ i = 1, 2, ..., 2n, \tag{9}$$

203 where n is the dimension of state variables, γ_i is a set of cubature points.

$$\gamma_i = \begin{cases} \sqrt{n}E_i, \ i = 1, 2, ..., n\\ -\sqrt{n}E_i, \ i = n+1, n+2, ..., 2n \end{cases}$$
(10)

where E_i is the unit matrix.

205 3). Cubature points propagation

$$x_{k+1|k}^{i} = f(x_{k}^{i}, u_{k}).$$
(11)

206 4). State prediction

$$\hat{x}_{k+1|k} = \frac{1}{2n} \sum_{i=1}^{2n} x_{k+1|k}^{i}, \qquad (12)$$

207

$$\bar{p}_k = \frac{1}{2n} \sum_{i=1}^{2n} x^i_{k+1|k} (x^i_{k+1|k})^T - \hat{x}_{k+1|k} (\hat{x}_{k+1|k})^T + Q.$$
(13)

²⁰⁸ 5). Cubature points calculation

$$\bar{p}_k = S_{k+1|k} S_{k+1|k}^T,$$
(14)

209

$$X_{k+1|k}^{i} = S_{k+1|k}\gamma_{i} + \hat{x}_{k+1|k}.$$
(15)

210 6). Cubature points propagation

$$y_{k+1}^{i} = h(X_{k+1|k}^{i}, u_{k}).$$
(16)

211 7). Measurement update

$$\hat{y}_{k+1} = \frac{1}{2n} \sum_{i=1}^{2n} y_{k+1}^i, \tag{17}$$

212

$$p_{yy} = \frac{1}{2n} \sum_{i=1}^{2n} y_{k+1}^{i} (y_{k+1}^{i})^{T} - \hat{y}_{k+1} \hat{y}_{k+1}^{T} + R, \qquad (18)$$

213

$$p_{xy} = \frac{1}{2n} \sum_{i=1}^{2n} X_{k+1|k}^{i} (y_{k+1}^{i})^{T} - \hat{x}_{k+1|k} \hat{y}_{k+1}^{T}.$$
 (19)





(b) The APE of PEMFC voltage estimation



(c) The estimation of PEMFC degradation state (α)

(d) The estimation of PEMFC degradation rate (β)

Figure 4: Degradation estimation based on CKF

²¹⁴ 8). State and covariance update: Estimate the Kalman gain K, state \hat{x}_{k+1} ²¹⁵ and covariance P_{k+1}

$$K = p_{xy} p_{yy}^{-1}, (20)$$

216

$$\hat{x}_{k+1} = \hat{x}_{k+1|k} + K(y_{k+1} - \hat{y}_{k+1}), \qquad (21)$$

$$P_{k+1} = \bar{p}_k - K p_{yy} K^T.$$
 (22)

The degradation state α and degradation rate β of the PEMFC degrada-218 tion model are estimated by the CKF. As shown in Fig.4(a), the estimated 219 voltage is close to the measured voltage of PEMFC. As shown in Fig.4(b), 220 the maximum Absolute Percentage Error (APE) between the measurement 221 voltage and CKF estimated voltage is less than 1.8%. The mean APE be-222 tween the measurement voltage and CKF estimated voltage is about 0.11%. 223 As shown in Fig.4(c), with the operation of the PEMFC, the degradation 224 state of the PEMFC increases. As shown in Fig.4(d), the mean degradation 225 rate is about 0.0003. The estimated degradation state and degradation rate 226 are applied to design the control systems. 227

228 4. Design of control strategy

229 4.1. Control Structure

The control structure of hybrid fuel cell/SCs power system is illustrated in Fig.5. The proposed control strategy is on the basis of a cascaded control loop.



Figure 5: Control structure diagram

As shown in Fig.5, the SCs reference current i_{sc}^* is transmitted by the DC bus and the SCs current i_{sc} is regulated by the bidirectional DC/DC controller with its own current controller. In the inner voltage loop, a twisting controller with an integrator and saturation functions is proposed in order to guarantee the convergence of the voltage of the DC bus at its reference value, while compensating the external perturbation; in the outer voltage loop, a
PI controller with an anti-windup scheme is utilized in order to regulate the
voltage of SCs at its nominal condition.

The complete hybrid fuel cell/ SCs system can be expressed as following equations:

$$\frac{d}{dt}v_b(t) = \frac{i_{fc}(t) + (1 - a_{sc}(t))i_{sc}(t) - i_l(t)}{C},$$
(23)

$$\frac{d}{dt}v_{sc}(t) = -\frac{i_{sc}(t)}{C_{sc}},\tag{24}$$

$$\frac{d}{dt}i_{sc}(t) = \frac{v_{sc}(t) - v_b(t)(1 - a_{sc}(t))}{L_{sc}},$$
(25)

$$i_{fc}(t) = \frac{V_{fc}(t) - v_b(t)}{R_{fc}(t)},$$
(26)

where a_{sc} is the duty cycle of the bidirectional DC/DC converter, $i_{fc}(t)$ is the current of fuel cell, $i_{sc}(t)$ is the current of SCs, $i_l(t)$ is the current of the load, $v_{sc}(t)$ is the voltage of SCs and $v_b(t)$ is the DC bus voltage, with state space $x(t) = [v_b; v_{sc}; i_{sc}]^T$, control input $u(t) = a_{sc}$, measurements $y(t) = [i_{fc}; i_{sc}; i_l; v_b; v_{sc}]$.

²⁴⁸ Considering the degradation of fuel cell, according to the degradation ²⁴⁹ model detailed in section 3, $V_{fc}(t)$ in equation (26) can be rewritten as fol-²⁵⁰ lowing equation:

$$V_{fc}(t) = E_r - ATln(\frac{i_{fc}(t)}{i_o}) - i_{fc}(t)R_{fc}(0)(1 + \alpha(t)) - BTln(\frac{i_{lim}(0)(1 - \alpha(t))}{i_{lim}(0)(1 - \alpha(t)) - i_{fc(t)}}) + \frac{i_{fc}(t)}{(27)} + \frac{i_{fc}(t)}{$$

where the degradation state $\alpha(t)$ can be expressed as βt , in which β represents the degradation speed of fuel cell.

In order to design the twisting controller for the inner voltage loop, the bandwidth of the bidirectional DC/DC converter current control loop is assumed as decoupled to the inner voltage loop. Thus, it can be deduced that the controller current of SCs is equal to the reference current of SCs which is calculated from the inner voltage loop on the basis of twisting controller. Under the previous assumption, the following equation can be obtained, as shown in equation (28).

$$L_{sc}\frac{d}{dt}i_{sc}(t) = 0.$$
(28)

Substitute equation (28) into the equation (25), then:

$$v_{sc}(t) - v_b(t)(1 - a_{sc}(t)) = 0.$$
(29)

²⁶¹ The above equation can be represented as follows.

$$a_{sc}(t) = 1 - \frac{v_{sc}(t)}{v_b(t)}.$$
(30)

Thus, the expression of the DC bus voltage is shown as equation (31) and (32), in which $i'_{sc}(t)$ is the new input variable in this reduced system currently.

$$C\frac{d}{dt}v_b(t) = i_{fc}(t) + i'_{sc}(t) - i_l(t), \qquad (31)$$

265 with

$$i'_{sc}(t) = \frac{v_{sc}(t)}{v_b(t)} i_{sc}(t).$$
(32)

266 4.2. Inner voltage controller

The main objective of the inner voltage loop is to regulate the DC bus voltage to its reference value while rejecting the external disturbance and taking into account the degradation of the PEMFC.

In this work, the inner voltage controller utilizes the idea of relative de-270 gree extension where the virtual control input is chosen as twisting controller. 271 This controller is well-known by its robustness in presence of system uncer-272 tainty and unexpected fluctuations [37]. Indeed, it provides a discontinuous 273 control signal and ensures the finite time convergence of the state variable 274 and its derivative to the origin for systems with relative degree two [38, 39]. 275 It has been widely used in different areas, such as power systems, power 276 converters, electrical drives and robot manipulators [40]. 277

In the considered hybrid power system, the dynamics of the DC bus voltage can be expressed as a first order disturbed system as shown in equation (31). Due to that and in order to implement the twisting controller algorithm, the idea of relative degree extension has been used. The application of this idea will be described now in detail. Let us first define $\phi(t) = i_{fc}(t) + i'_{sc}(t) - i_l(t)$ as a new auxiliary state, then the dynamics of the DC bus voltage given by equation (31) can be expressed as

$$C\frac{d}{dt}v_b(t) = \phi(t),$$

$$\dot{\phi}(t) = v(t),$$
(33)

where v(t) is the new virtual control input to be designed. Now, let us define the sliding variable $s_{vb}(t)$ and its derivative $s_{\phi}(t)$ for the DC bus voltage as follows

$$s_{vb}(t) = C(v_b(t) - v_b^*(t)), s_{\phi}(t) = \phi(t) - C\dot{v}_b^*(t),$$
(34)

where $v_b^*(t)$ is the reference DC bus voltage obtained from the outer voltage loop and that will be designed later. Taking the first derivative of $s_{vb}(t)$ and $s_{\phi}(t)$, we obtain

$$\begin{aligned} \dot{s}_{vb} = s_{\phi}, \\ \dot{s}_{\phi} = \delta(t) + v(t), \end{aligned} (35)$$

where $\delta(t)$ is the total disturbance caused by parameter uncertainties, i.e. the degradation of the PEMFC and the external disturbance. For example, if $\ddot{v}_b^*(t)$ is not compensated, we would have $\delta(t) = -C\ddot{v}_b^*(t)$.

For system (35), the standard twisting control algorithm given by [22]

$$v(t) = -K_1 sign(s_{vb}) - K_2 sign(s_{\phi}), \qquad (36)$$

drives both s_{vb} and s_{ϕ} to zero in a finite time, i.e. it provides the convergence of the DC bus voltage to its reference value if the control gains are chosen as $K_1 = \Upsilon$ and $K_2 = 0.5\Upsilon$ where $\Upsilon > 2\delta_{max}$ with $|\delta(t)| \leq \delta_{max}$.

The proof of the above statement using strict Lyapunov functions can be founded in [23, 41]. On the other hand, one can follow [22] and ensure the convergence of the twisting algorithm using a geometrical proof.

It should be noted that the application of this controller requires the assumption that the information of the load current is available. This assumption is frequently used in such domain as we can see in [4, 42].

305 4.3. Outer voltage controller

The main objective of the outer voltage loop focuses on controlling the 306 SCs voltage by controlling the current of fuel cell indirectly and thereupon 307 the DC bus voltage. As shown in Fig.5, the fuel cell current will be indi-308 rectly regulated by the variation of the DC bus voltage so as to keep the SCs 309 current at its desired operating value. Referring to equation (1), the rela-310 tionship between $i_{fc}(t)$ and $v_b(t)$ is nonlinear. Thus, the outer voltage loop is 311 considered to utilize a small-signal model approach, which means that near 312 the operating point of fuel cell, the linearization is made for equation (1). 313 Then, the variation relationship between $\delta i_{fc}(t)$ and $\delta v_b(t)$ can be presented 314 as follows. 315

$$\delta i_{fc}(t) = -H\delta v_b(t),\tag{37}$$

where H is a positive parameter with the range of $[H_{min}, H_{max}]$.

The outer voltage controller is on the basis of PI controller, which is designed as follows.

$$v_b^* = k_p (v_{sc}^* - v_{sc}) + k_i \int (v_{sc}^* - v_{sc}) dt, \qquad (38)$$

where k_p is the gain of the proportional term and k_i is the gain of the integral term.

321 4.4. Limitation constraints

In order to ensure the security of fuel cell and SCs, some limitation constraints are taken into account in the proposed control strategy. These constraints are integrated as dynamic saturation functions for the inner and the outer voltage loops.

In this paper, the constraint of SCs current is a dynamic saturation process, which can be illustrated in Fig.6.

The security voltage range of SCs is presented in equation (39). Within this security range, the security thresholds of SCs reference voltage are defined as equation (40) so as to guarantee the safe operation of SCs in charge mode and in discharge mode.

$$v_{sc} \in [v_{sc_min}, v_{sc_max}] \tag{39}$$

$$v_{sc}^* \in [v_{sc_low}, v_{sc_high}] \tag{40}$$



Figure 6: Limitation constraints of SCs current

In Fig.6, the red curve shows the SCs operates in discharge mode. If SCs voltage reaches $v_{sc.low}$, the absolute value of SCs reference current will decrease very soon until SCs voltage reaches $v_{sc.min}$. On the other hand, the blue curve shows the SCs operates in charge mode. When the SCs voltage reaches $v_{sc.high}$, the absolute value of SCs reference current will drop rapidly until SCs voltage reaches $v_{sc.max}$.

The limitations of SCs reference current mentioned above are presented as mathematical expressions equation (41) and (42). These two constraints are integrated in the saturation scheme of the inner voltage loop so as to avoid the occurrence of integral saturation.

$$i_{sc_max_cha} = i_{max} \cdot max \left(-1, min\left(0, \frac{v_{sc} - v_{sc_max}}{v_{sc_max} - v_{sc_high}} \right) \right)$$
(41)

$$i_{sc_max_dis} = i_{max} \cdot min\left(1, max\left(0, \frac{v_{sc} - v_{sc_min}}{v_{sc_low} - v_{sc_min}}\right)\right)$$
(42)

Moreover, the constraints of fuel cell current are integrated in the antiwindup scheme of the outer voltage loop in order to prevent the integral saturation. Due to the fact that the fuel cell is linked to the load directly, the current of fuel cell cannot be controlled directly. Therefore, the DC bus voltage is adjusted between the dynamic security thresholds $[v_{b_min_dyn}, v_{b_max_dyn}]$, so as to limit the fuel cell discharge current in the security range $[v_{b_min}, v_{b_max}]$, as shown in the following equations.

$$v_{b_max_dyn} = v_b^* + K_{ifc} i_{fc}(t), \tag{43}$$

$$v_{b_min_dyn} = v_b^* + K_{ifc}(i_{fc}(t) - i_{fc_max_dis}).$$

$$(44)$$

349 5. HIL test results

The proposed control strategy for the single converter hybrid fuel cell/SCs 350 power system taking into consideration the PEMFC degradation is validated 351 by a HIL test bench. This test bench consists of two dSPACE DS1104 real-352 time board cards as shown in Fig.7. One dSPACE is used as hardware 353 controller to implement the proposed control strategy and to validate its fea-354 sibility in real time. On the other hand, the other one is utilized as emulator 355 to emulate the single converter hybrid fuell cell/SCs power system. For the 356 realization of the HIL test bench, we have used a sampling frequency of 10 357 kHz for both dSPACE cards [43]. The degradation rate estimated in section 358 3 is adopted in the HIL test system. For SCs, the initial reference voltage 359 v_{scref} is set as 125V, v_{sc_min} and v_{sc_low} are set as 0.5 v_{scref} and 0.75 v_{scref} 360 respectively, v_{sc_max} and v_{sc_high} are set as 136V and 131V respectively. For 361 fuel cell, the discharge limitation current $i_{fc_max_dis}$ is set as 80A. For DC bus 362 voltage, the security range is set as [26V, 38V]. 363



Figure 7: Scheme of HIL test system

In this section, the HIL test results are carried out by connecting the load affected by perturbations to the hybrid fuel cell/SCs power sources. The load current curve adopted in this HIL test is a superposition of a step demand current curve and a sinusoidal perturbation current curve. The frequency and amplitude of the sinusoidal perturbation current are 7.5Hz and 3A respectively.

³⁷⁰ 5.1. HIL test results of the proposed control strategy

The HIL test results of the proposed control strategy for hybrid fuel cell/SCs power system are shown in Fig.8 and Fig.9. According to these two figures, after utilizing the proposed control strategy, the perturbations on fuel cell current have been attenuated to a large extent due to the fact that SCs absorb the transient and sinusoidal perturbations effectively. The control strategy proposed in this paper can smooth the behavior of fuel cell current, which benefits to the lifespan of PEMFC.

Fig.8 presents the condition in nominal mode, in which all of the current 378 and voltage values are in the allowed range. The dynamic DC bus voltage 379 thresholds keep constant all the time, which means the saturation function 380 is not activated. As shown in Fig.8(a), (c), (d), at the time of 10s and 140s. 381 with the sudden increase of the load current, SCs operate as the auxiliary 382 power source discharges rapidly and provide the current in transient process. 383 Subsequently, the fuel cell with lower dynamic operates as the main power 384 source. On the other hand, when the load current decreases suddenly at the 385 time of 70s and 210s, the mode of SCs changes to the charge mode quickly. 386 After that, fuel cell works as the main power source. Moreover, the value 387 of SCs voltage is regulated at the desired security operating range and the 388 convergence of DC bus voltage is validated for the proposed control method. 389 Fig.9 presents the condition when the fuel cell discharge current reaches 390 the limitation threshold. In this condition, the saturation function is acti-391 vated so as to protect the fuel cell. As shown in Fig.9(c), from 10s to 70s, 392 the fuel cell current is limited at $i_{fc_max_dis}$, namely the value of 80A. 393

³⁹⁴ 5.2. Comparison with HIL test results of two PI controllers method

In order to make further analysis of the proposed control strategy, the HIL tests of the same hybrid fuel cell/SCs power system with two PI controllers are implemented as well. In other words, the HIL tests are made after replacing the twisting controller with the integrator in inner voltage loop by a traditional PI controller and the outer voltage loop adopts PI controller still. Fig.10 presents the comparison HIL test results of fuel cell current between the traditional method on the basis of two PI controllers and the proposed



(e) Super capacitors voltage v_{sc} and error e_{vsc}

Figure 8: HIL test results in nominal mode



Figure 9: HIL test results in discharge limitation mode

control method which is based on one twisting controller used in inner volt-402 age loop and one PI controller used in the outer loop. It can be seen that the 403 oscillations of fuel cell current by the proposed method are smaller than two 404 PI method. For proposed method, the oscillation amplitude of the sinusoidal 405 oscillations on the fuel cell current is 0.165A; for two PI method, the oscilla-406 tion amplitude of the sinusoidal oscillations on the fuel cell current is 0.86A. 407 That is to say, the fuel cell current of the proposed method is smoother than 408 the method of two PI controllers. 409

The change of fuel cell current will bring challenges to fuel cell water 410 management, thermal management and gas management [44, 45]. Moreover, 411 the changing fuel cell current will accelerate the degradation of the fuel cell 412 membrane, catalyst and gas diffusion layer [45, 46]. For example, the chang-413 ing current will cause the catalyst particles to become coarse and lead to the 414 change of the oxide coverage degree of platinum and carbon, and the surface 415 hydrophobicity [47, 48]. In addition, the durability comparison experiments 416 show that the degradation rate of fuel cells under constant current is lower 417 than that of fuel cells under dynamic current with oscillations [49]. Overall, 418 the smoother fuel cell current results in the lower degradation rate, which is 419 better for the lifespan of fuel cells. Hence, compared with two PI controllers 420 method, our proposed method can increase the lifespan of fuel cell better. 421

Therefore, the proposed method in this paper based on the combination of twisting controller and PI controller is better than the control method based on two PI controllers in terms of perturbation suppression.

425 6. Conclusion

In this paper, considering the degradation of PEMFC, a novel second 426 order sliding mode control strategy for hybrid fuel cell/super capacitors power 427 system on the basis of only one converter has been presented. In this hybrid 428 power system, fuel cell and super capacitors are performed as the main source 429 and auxiliary source respectively. The degradation state and degradation 430 rate of the PEMFC degradation model are estimated using the CKF method 431 and are taken into account in the hybrid system. In this hybrid system, 432 the proposed control strategy utilizes the twisting controller for the inner 433 voltage loop and the proportional integral controller for the outer voltage 434 loop. Moreover, some limitation constraints are taken into account so as to 435 protect and increase the lifespan of the hybrid power sources. Finally, the 436 effectiveness of the proposed control strategy is verified by HIL test bench. 437



(d) Proposed method - in discharge limitation mode

Figure 10: Comparison of the proposed method and two PI controllers method - Fuel cell current i_{fc}

In future research work, there are two aspects which will be considered. Firstly, consider to design the adaptive version of the current algorithm in order to avoid overestimating the gains. Secondly, try to propose an algorithm that does not need the information of load current which is considered as an unknown perturbation.

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