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Fuzzy/State-Feedback Control of a Non-Inverting Buck-Boost Converter for Fuel Cell Electric Vehicles

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Abstract: This paper presents an intelligent state feedback controller of a non-inverting buck-boost converter for fuel cell power sources. The proposed control strategy uses fuzzy logic control and state feedback control in order to combine advantages of both controllers. Fuel cell DC/DC converters often have to be able to both step-up and step-down the input voltage and provide a high efficiency in the whole range of output power. Non-inverting buck-boost converters provide both step-up and step-down characteristics. In this paper a state-space average model of converter is obtained and the effect of using a state feedback controller in order to stabilize and regulate the output voltage has been proposed. The use of intelligent state feedback controller allows choosing the proper pole placement of system and using inductor current as a feedback provides a fast dynamic response. Simulation results showed the capability of proposed control strategy during different conditions in fuel cell electric vehicles.

Key words: Fuzzy control · State feedback control · DC-DC converter · Fuel Cell · Electric Vehicle

INTRODUCTION

Due to wide variation of fuel cell output voltage, it is often necessary either to step-up or step-down the fuel cell voltage. Fuel cells have a high efficiency at low output current and it is therefore advantageous to operate them at a low power level; e.g. when charging the batteries in a fuel cell hybrid electric vehicle application, in order to save fuel. However, during periods with high power demands it is necessary to operate them at rated power [1, 2]. As fuel cells are operated in a wide variation of power, it is important that the DC/DC converters not only have a high efficiency at nominal power, but also in the whole power range [3, 4]. Several topologies are capable of both step-up and step down the fuel cell voltage [5]. Due to its simplicity, low component stress and high efficiency it is chosen to use the non-inverting buck-boost converter [6]. In this paper expression of the non-inverting buck-boost converter is therefore derived when parasitic losses are taken into account. Recently in literature, some studies have been developed for controlling of this type of DC-DC converter [4, 7]. Mostly, classic and state feedback control strategies have been designed for non-inverting buck-boost converter. The "min" disadvantage of these control strategies is that they work on fixed operating point. Meanwhile if the input voltage of converter or load current change, the designed controller could not operate well. Also, the disadvantages of conventional buck-boost converters are right half plane (RHP) zeros which restrict the controller response [8, 9]. Hence, a control strategy should be developed in order to tolerate of these limitations. For this purpose, in this paper hybrid fuzzy/ state feedback controller is developed for non-inverting buck-boost converter. This controller technique has the advantages of more robustness and faster dynamics compared to PI or PID conventional controllers.

Based on above justifications, the feasibility of the non-inverting buck-boost converter for fuel cell applications is investigated. This paper is organized as follows. The single inductor non-inverting buck-boost converter is proposed. In section II, a state space average model of converter is obtained and in the next part (section III) hybrid fuzzy/ state feedback controller is designed.

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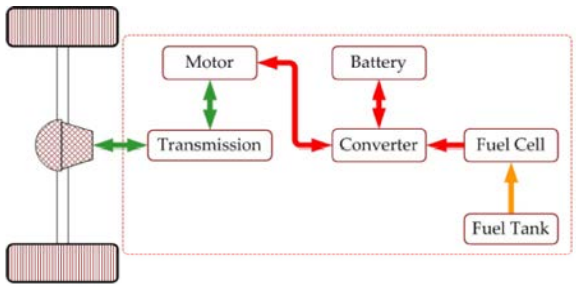

Fig. 1: Schematic block diagram of Fuel Cell and supportive controlling units

Dynamic Model of Fuel Cell Electric Vehicle: The model in a Fuel Cell Electric Vehicle (FCEV) is an important issue that needs to be carefully addressed. The electric components of a FCEV used in this paper comprise a battery bank, Non-inverting buck-boost DC/DC converter, while the electrochemical component is a Fuel Cell system (FC). The mathematical models describing the dynamic behavior of each of these components are given as follow [10]. Fig. 1 illustrates the supportive controlling units of fuel cell system in an electric vehicle.

Fuel Cell Model: Fuel cells are static energy conversion devices that convert the chemical energy of fuel directly into electrical energy. They show great promise to be an important power source of the future due to their number of advantages, such as high efficiency, zero or low emission (of pollutant gases) and flexible modular structure. The model of Polymer Exchange Membrane Fuel Cell (PEMFC) power plant used in this study is based on the dynamic PEMFC stack model developed and validated in literature [4]. The performance of FCs is affected by several operating variables, as discussed in the following. Decreasing the current density increases the cell voltage, thereby increasing the FC efficiency. One of the important operating variables is the reactant utilization or direct uptake of the energy yield restored in the fuel molecules, U_f, referring to the fraction of the total fuel (or oxidant) introduced into a FC that reacts electrochemically:

$$U_f = \frac{q_{H_2}^{in} - q_{H_2}^{out}}{q_{H_2}^{in}} = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} \qquad (1)$$

Where q_{H2} is the hydrogen molar flow.

High utilizations are considered desirable (particularly in smaller systems) because they minimize the required fuel and oxidant flow, for a minimum fuel cost and compressor load and size. However, utilizations that are pushed too high result in significant voltage drops. The PEMFC consists of hundreds of cells connected in series and parallel. Fuel and air are passed through the cells. By regulating the molar flow rate, the amount of fuel fed into the fuel cell stacks is adjusted and the output real power of the fuel cell system is controlled. The Nernst's equation and Ohm's law determine the average voltage magnitude of the fuel cell stack [11]. The following equations model the voltage of the fuel cell stack:

$$V_{fc} = N_0(E_0 + \frac{RT}{2F}(\ln(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}})) - rI_{f0} \qquad (2)$$

Where, N_0 is the number of cells connected in series; E_0 is voltage associated with the reaction free energy; R is the universal gas constant; T is the absolute temperature; I_{f0} is the current of the fuel cell stack; F is the Faraday's constant. r is internal resistance of fuel cell. P_{H2}, P_{H2O}, P_{O2} are hydrogen, water and oxygen pressures which determined by the following differential equations [1, 11]:

$$\begin{aligned} \dot{P}_{H_2} &= -\frac{1}{t_{H_2}}(P_{H_2} + \frac{1}{K_{H_2}}(q_{H_2}^{in} - 2K_r I_{fc})) \\ \dot{P}_{H_2O} &= -\frac{1}{t_{H_2O}}(P_{H_2O} + \frac{2}{K_{H_2O}}K_r I_{fc})) \\ \dot{P}_{O_2} &= -\frac{1}{t_{O_2}}(P_{O_2} + \frac{1}{K_{O_2}}(q_{O_2}^{in} - K_r I_{fc})) \end{aligned} \qquad (3)$$

Where, $q_{H_2}^{in}$ and $q_{O_2}^{in}$ are the molar flow of hydrogen and oxygen;

K_r constant is defined by the relation between the rate of reactant hydrogen and the fuel cell current

$$q_{H_2}^{r} = \frac{N_0 I}{2F} = 2K_r I \qquad (4)$$

Non-Inverting Buck-Boost Converters: The circuit diagram of non-inverting buck-boost is shown in Fig. 2. The converter consists of one inductor, one output capacitor, two MOSFET switches and two diodes. A non-inverting buck-boost converter consists of two cascade buck and boost converter which can work in three different mode. When the output voltage is higher than the input; it can work in boost region, as the input voltage decrease; it works in buck-boost mode when input voltage is within the range of output. Finally, if the output voltage is much lower than inputs it is in buck region [3].

If S_1 is on and the duty cycle of S_2 is controlled the converter operates like a boost converter and if S_2 is off and duty cycle of S1 is controlled the converter is like a

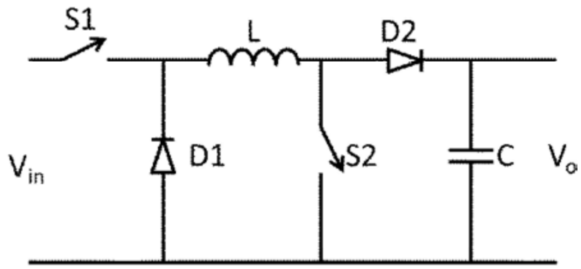

Fig. 2: Non-inverting Buck-Boost Converter topology

buck with a forward diode voltage drop. In the steady state the relation between the input and output voltage is obtained by the following formula:

$$\frac{V_O}{V_{in}} = \frac{D_1}{(1-D_2)} \begin{cases} D_1 + D_2 > 1 \rightarrow Boost \\ D_1 + D_2 < 1 \rightarrow Buck \end{cases} \quad (5)$$

Which D_1 is the duty cycle of buck switch and D_2 is the duty cycle of boost switch. In order to avoid short circuit of the input with the inductor, D_1 is always greater than D_2.

In order to determine the state space model of switching converters we need to consider the circuit in different conditions based on the allowable switching scheme. In this converter there are three different situations stated as follows.

- Both S_1 and S_2 is on ($0<t<D_2T$)
- S_1 is on and S_2 is off ($D_2T<t<D_1T$)
- Both switches are off

$$(a) \begin{cases} \frac{dv_C}{dt} = \frac{1}{C}\left(-\frac{v_C}{R}\right) \\ \frac{di_L}{dt} = \frac{1}{L}(v_{in}) \end{cases} \quad 0 < t < D_2T$$

$$(b) \begin{cases} \frac{dv_C}{dt} = \frac{1}{C}\left(i_L - \frac{v_C}{R}\right) \\ \frac{di_L}{dt} = \frac{1}{L}(v_{in} - v_C) \end{cases} \quad D_2T < t < D_1T$$

$$(c) \begin{cases} \frac{dv_C}{dt} = \frac{1}{C}\left(i_L - \frac{v_C}{R}\right) \\ \frac{di_L}{dt} = \frac{1}{L}(-v_C) \end{cases} \quad D_1T < t < T$$

Where i_L is the inductor current, v_c is the capacitor voltage, v_{in} is the input voltage of converter and R is the load resistance. The uppercase variables are equilibrium of converter [3-5].

With the combination of these three equations and linearization around equilibrium operating point the average state space model of converter is obtained.

Table 1: The DC-DC converter parameters

L	100uH
C	1000uF
v_{in}	5V
R	12V
Fs	1 Ω
	50kHz

In order to simplify the model suppose that the converter always operates in buck-boost region and duty cycle of S1 and S2 are equal. The simplified state space average model will be obtained [6]:

$$\begin{pmatrix} \frac{d\hat{v}_C}{dt} \\ \frac{d\hat{i}_L}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{1}{RC} & \frac{(1-D)}{C} \\ -\frac{(1-D)}{L} & 0 \end{pmatrix} \begin{pmatrix} \hat{v}_C \\ \hat{i}_L \end{pmatrix} + \begin{pmatrix} -\frac{I_L}{C} \\ \frac{V_{in}+V_c}{L} \end{pmatrix} \hat{d} + \begin{pmatrix} 0 \\ \frac{D}{L} \end{pmatrix} \hat{v}_{in} \quad (6)$$

State Feedback Control Design: Before designing state feedback controller it is needed to choose a proper operating point for converter. The converter parameters are shown in Table 1.

With the above component data the state space model of converter in the form of $\dot{X} = AX + BU + \Gamma W$ will be:

$$\begin{pmatrix} \frac{d\hat{v}_C}{dt} \\ \frac{d\hat{i}_L}{dt} \end{pmatrix} = \begin{pmatrix} -1667 & 294 \\ -2941 & 0 \end{pmatrix} \begin{pmatrix} \hat{v}_C \\ \hat{i}_L \end{pmatrix} + \begin{pmatrix} -48000 \\ 170000 \end{pmatrix} \hat{d} + \begin{pmatrix} 0 \\ 7059 \end{pmatrix} \hat{v}_{in} \quad (7)$$

Where U is input vector of system and W is disturbance vector. First step of designing state feedback controller is checking the controllability of the system [12]. By foundation of the controllability matrix (*V*), it is shown that it is full rank and the determinant of V is not zero so the system is controllable.

$$V = [A \quad AB] = \begin{bmatrix} 0 & 1.3*10^8 \\ 7059 & 1.41*10^8 \end{bmatrix} \quad (8)$$

With this data parameters the two poles of system are at S_1=-833+413i and S_2=-833-413i. Then the open loop system is stable, but according to the time response it has to be compensated. The step response of closed loop system to a step change in the input voltage is shown in Fig. 3. Where k_1= 0.1 is the gain of the capacitor's voltage feedback and k_2=0.05 is the gain of inductor current feedback. Hence, the control signal is calculated by following equation:

$$U = -KX(t) = \begin{bmatrix} -k_1 \\ -k_2 \end{bmatrix}^T \cdot \begin{pmatrix} \hat{v}_C \\ \hat{i}_L \end{pmatrix} \quad (9)$$

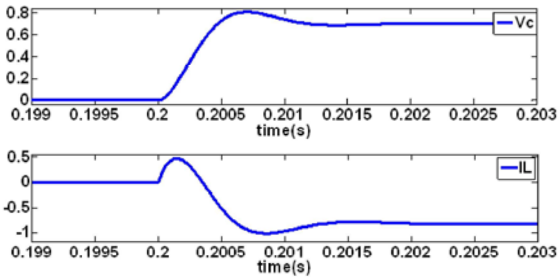

Fig. 3: Step response of system with state feedback controller

As it is shown if Fig. 3, the state feedback the whole system is stable but it is desired with a step change in the input voltage the output voltage remain constant and v_c should be near zero after the step change but the inductor current will converge to a new vaue.

Using state feedback controller by itself cannot regulate the output voltage but it has improved stability and time response so, it is needed to add an integrator term to the voltage controller loop. The step response of system with the new controller to a step change in the input voltage is shown in Fig. 4. It shows that with a proper integrator gain the output voltage remains constant while the input has changed and the inductor current will decrease as the input voltage increase.

With a state feedback controller and a voltage regulator not only the system is stable but also it has a fast and correct step response. A step change in the input voltage will force the output to rise but it reaches zero after a settling time.

Hybrid Fuzzy/ State-Feedback Control Strategy: In fuel cell power generation systems, the output voltage of fuel cell changes during the different load currents. In fact, the operating point conditions of DC-DC converter are not constant. So, it is important to design a flexible control strategy for DC-DC converter to operate under different conditions. Hence, in this paper, a robust self-tuning fuzzy control structure has been developed [13]. The block diagram of the hybrid fuzzy/ state feedback controller is shown in Fig. 5.

Use of the scaling factors (SFs) G_e, $G_{\Delta e}$, the quantities e and Δe are converted to normalized e_N and Δe_N. These normalized quantities e_N and Δe_N are crisp in nature and therefore need to be first converted to their corresponding fuzzy variables. After fuzzification, the fuzzified inputs are given to the fuzzy inference mechanism which, depending on the given fuzzy rule

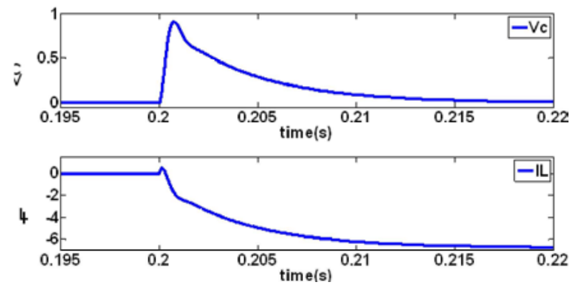

Fig. 4: Step response with state feedback controller and output voltage reugulator

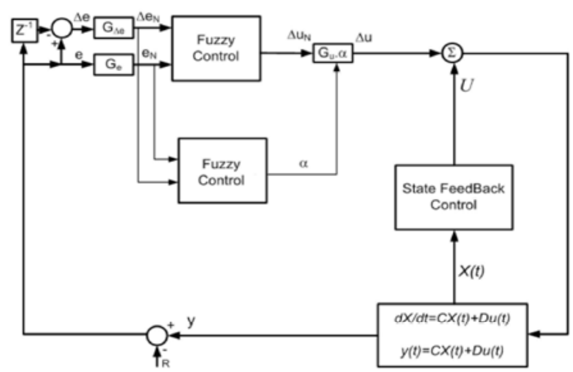

Fig. 5: Block diagram of the hybrid fuzzy/ state feedback controller

base, gives the normalized incremental change in control output (Δu_N). The output Δu_N is converted into actual incremental change in control output (Δu) by using the scaling factor Gu. For the implementation the fuzzy inference engine, the "min" operator for connecting multiple antecedents in a rule, the "min" implication operator and the "max" aggregation operator have been used [13]. Actually, the output Δu_N from the inference mechanism is fuzzy in nature, hence, to determine the crisp output, the defuzzification stage is applied. The centroid defuzzification scheme has been used here for obtaining the output Δu. Finally, the actual value of the controller output (u) is computed by the following expression:

$$u(k) = u(k-1) + \Delta u(k) \tag{10}$$

The relationships between the SFs and the input and output variables of the self-tuning FLC are as follow:

$$\begin{aligned} e_N &= G_e.e \\ \Delta e_N &= G_{\Delta e}.\Delta e \\ \Delta u &= (\alpha.G_u).\Delta u_N \end{aligned} \tag{11}$$

In this scheme, the FLC is tuned on-line (while the controller is in operation) by dynamically adjusting its output scale factor by a gain updating factor (α). The value of α is determined from a rule base defined on e and Δe which are derived from the knowledge of control engineering. Generally, selection of suitable values for G_e, $G_{\Delta e}$ and Gu are made based on the knowledge about the process to be controlled and sometimes through trial and error to achieve the best possible control performance.

Each fuzzy control rule in the controller rule base is of the form:

"If e is E and Δe is ΔE, then Δu is ΔU"

where E, ΔE and ΔU are the fuzzy sets corresponding to error, change in error and the incremental change in the control output, respectively. In this work, for both the inputs (e and Δe) and the output (Δu), seven fuzzy subsets have been used. These are: PB (positive big), PM (positive medium), PS (positive small), ZE (zero), NS (negative small), NM (negative medium) and NB (negative big). For each of these fuzzy sets, triangular membership function (MF) has been used.

From this figure it is observed that the triangles are symmetric with equal base having 50% overlap with neighboring MFs. As each of the two inputs has seven fuzzy sets, there are altogether 49 control rules in the FLC. The rule base for computing the output Δu is shown in Table 2 which is a widely used rule base designed with a two dimensional phase plane. The control rules in Table 3 are built based on the characteristics of the step response.

Moreover, the gain updating factor (α) is calculated using fuzzy rules of the form:

If e is E and Δe is ΔE then α is α.

From Fig. 6 it is observed that the value of α is computed from the normalized values of e and Δe by a fuzzy rule base. The membership functions used for e and Δe are exactly the same as those used in FLC. Moreover, the same fuzzy operators also been used in this case. The membership functions for the factor α are defined in the domain (0, 1). As each of the two inputs (e and Δe) to the fuzzy rule base (corresponding to α) has seven fuzzified variables, the rule base has 49 rules for computing the value of α. Table 4 shows the rule base for computing α. This rule base is designed to improve the control performance under large

Table 2: Rule base for computing the output Δu

Δe/e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

Table 3: Rule base for computing the output a

Δe/e	NB	NM	NS	ZE	PS	PM	PB
NB	VB	VB	B	SB	S	S	ZE
NM	VB	VB	B	B	MB	S	VS
NS	VB	VB	B	VB	VS	S	VS
ZE	S	SB	MB	ZE	MB	SB	S
S	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
*PB	ZE	S	SB	B	VB	VB	VB

disturbances such as three-phase short circuit on the transmission lines, a sudden loss of generating unit or a large loss of load, etc. For example, immediately after a large disturbance, e may be small but Δe will be sufficiently large (they will be of same sign) and, for this case, α is supposed to be large to increase the gain. Therefore, under these circumstances, the appropriate rules are "IF e is PS and Δe is PM THEN ² is B" or "IF e is NS andΔe is NM THEN α is B". On the other hand, for steady state conditions (i.e. $e \approx 0$ and $\Delta e \approx 0$), controller gain should be very small (e.g. IF e is ZE and Δe is ZE THEN α is ZE) to avoid chattering problem around the set point. Further justification for using the rule base in Table 3 found in literature [9].

Simulation of Results and Validation: In order to verify the mathematical model of fuel cell, converter and controller the whole system has been simulated in MATLAB software environment. It is supposed that fuel cell is supplied 5KW of active power. Moreover, it is assumed that the output voltage of DC-DC converter should be regulated at 100V under different load current conditions. For analyzing fuel cell power generation system with designed control strategy, three cases for simulation conducted that described as continue.

Control of fuel cell power system under different load conditions: For this purpose, load current changes as shown in Fig. 6. In Figs. 6 and 7 variations of fuel cell current and voltage are presented. As shown, the fuel cell voltage varies during current variations. So it needs to regulate this voltage under different loading conditions.

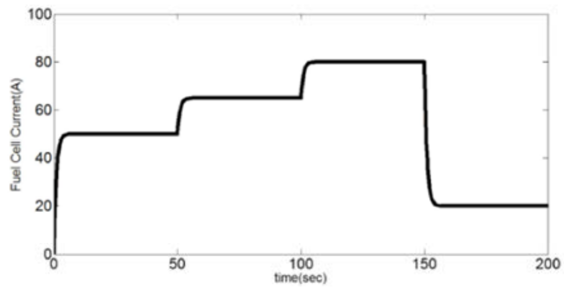

Fig. 6: Fuel cell current variations

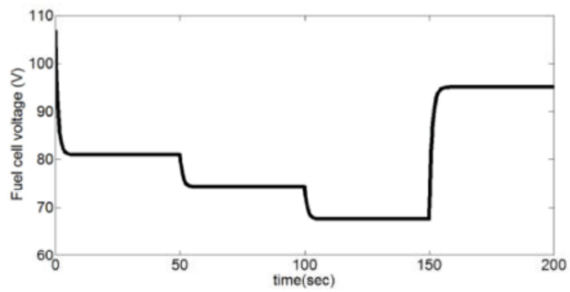

Fig. 7: Fuel cell voltage variations

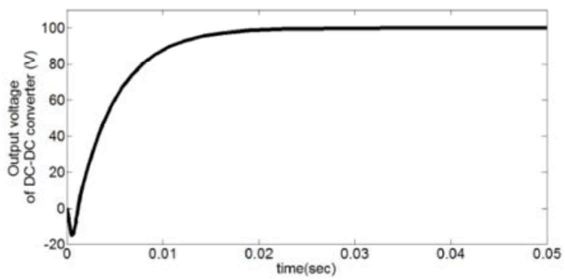

Fig. 8: Output voltage of DC-DC converter

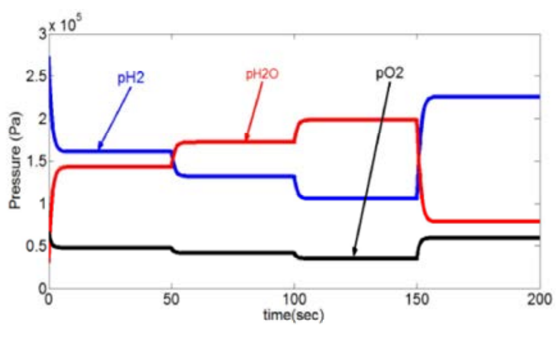

Fig. 9: Variation of hydrogen, oxygen and water pressures

Moreover, the output voltage of DC-DC converter is illustrated in Fig. 8. As it is shown, this voltage is controlled very fast under variations of fuel cell voltage. Because of non-minimum phase characteristic of DC-DC converter, there is undershoot at the fist time of simulation.

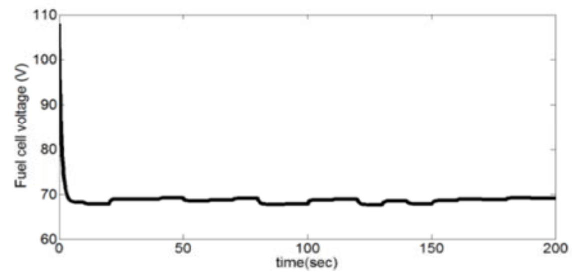

Fig. 10: Perturbed fuel cell voltage

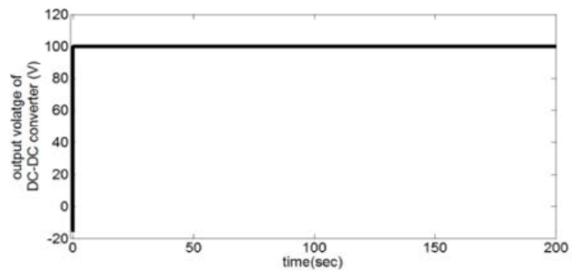

Fig. 11: Regulated output voltage of DC-DC converter

In order to show the dynamics of fuel cell during simulation, the variation of hydrogen, oxygen and water pressures are shown in Fig. 9.

In order to show the robustness of the hybrid fuzzy/state feedback control, a disturbance is added to input hydrogen fuel flow in order to perturb fuel cell voltage as shown in Fig. 10. In this case, supposed that the fuel cell current is constant (80A), but there are variations in voltage of fuel cell. In this case, output voltage of DC-DC converter is presented in Fig. 11.

Implementation of Proposed Control Strategy in Fuel Cell Hybrid Vehicle: According to the presented results, it is achieved that the proposed control strategy is very suitable for fuel cell power generation system. In fact, by this control strategy the output voltage of fuel cell is regulated under different loading conditions and existing disturbances which may occur in fuel cell stack. Moreover, this control strategy is proper for fuel cell hybrid vehicle during requested power from duty cycle. For this purpose, a simulation of results is conducted based on research work in literature [1, 10]. The requested power from fuel cell stack during standard driving cycle of ECE [14] has been implemented to show the response of DC-DC converter. In Fig. 12 variations of fuel cell current and voltage are illustrated.

In this condition, regulated voltage of DC-DC converter is presented in Fig. 13.

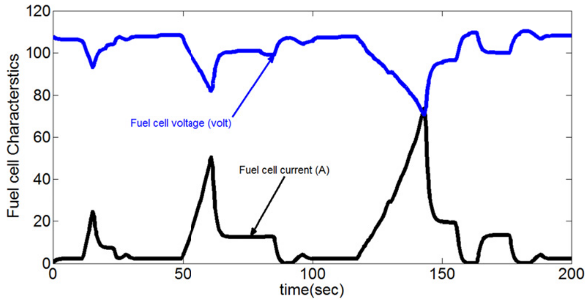

Fig. 12: Variations of fuel cell current and voltage in fuel cell hybrid vehicle

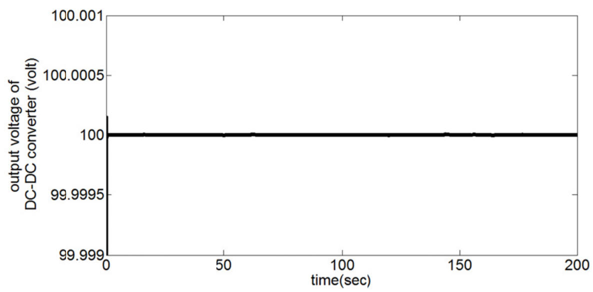

Fig. 13: Output voltage of DC-DC converter in fuel cell hybrid vehicle

CONCLUSION

A non-inverting buck boost with a hybrid fuzzy/ state feedback control method was introduced in this paper. It shows that using hybrid fuzzy/state feedback controller improves the system response. In fact, state feedback controller is designed based on fixed operating point of DC-DC converter. Fuzzy controller regulates the response of dynamic system when operating point of DC-DC converter changes which makes during input voltage or load current variation Moreover, a current sensor and a voltage sensor must be added in order to measure the system states. An external voltage controller was designed in order regulate the output voltage during any disturbances in the input voltage or output load. Comparing the output characteristics of a state space feedback to a conventional PI controller it has been shown that state space feedback controller has a better dynamic response but the steady state response are as the same.

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چکیده

در این مقاله یک روش کنترل فیدبک حالت هوشمند برای مبدلهای افزاینده-کاهنده غیر معکوس به منظور اتصال به منابع تولید توان پیل سوختی ارائه می شود. روش کنترل پیشنهادی ترکیبی از یک کنترل کننده فازی و کنترل فیدبک حالت می باشد که باعث می شود از ویژگیهای هر دو بتوان استفاده کرد. مبدلهای DC-DC مرتبط به پیلهای سوختی در خودورهای برقی نیاز دارند تا براساس نیاز عملکردی در آنها بتوانند ولتاژ را افزایش و کاهش دهند. لذا مبدلهای افزاینده= کاهنده غیر معکوس انتخاب مناسبی برای این کاربرد می باشد. در این مقاله ابتدا مدل میانگین غیر خطی مبدل استفاده می شود. سپس در یک نقطه کار مشخص، کنترل کننده فیدبک حالت به منظور پایدار سازی و تنظیم ولتاژ خروجی در نقطه کار طراحی می گردد. سپس سعی می گردد تا با یک کنترل کننده فازی تغییرات نقطه کار در ولتاژ خروجی را کنترل نمود. نتایج شبیه سازی براساس پیاده سازی این مبدل در خودورهای برقی پیل سوختی نشان می دهد که کنترل کننده طراحی شده قادر است تا تحت شرایط عملکردی مختلف، سیستم مورد نظر را درستی کنترل نماید.