USING DYNAMIC MODEL OF PEM-FUEL CELL SUPPLYING THE LOAD BY THE Z-SOURCE INVERTER WITH A NOVEL CONTROL STRATEGY

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Abstract
A new dynamic model is developed in this paper to connect PEM Fuel Cell (PEMFC) to a Z-source inverter (ZSI). This model is used to analyse the behaviour of a fuel cell by providing a polarization curve. A controller is designed based on an interpolation to spot parameters of PEM Fuel Cell such as temperature (or anode and cathode pressure). A current feedback is gained to regulate the output voltage through determination of physical parameters. The ZSI is used in the proposed model to generate AC power. In this research, to compensate the voltage drop of fuel cell the capacitor voltage of the Z-network is controlled using the state space averaging method to stabilize the AC output voltage of the ZSI. Simulation and experimental results verify the validity of the proposed controlling model.

Keywords - Z-Source Inverter; PEM-Fuel Cell; Shoot-through; state space averaging model

1. Introduction

The voltage of a Fuel Cell (FC) is a nonlinear function of current, temperature, Oxygen, and the fuel pressure associated with the FC. In [1], the authors proposed a FC model considering a constant RC for connecting to a ZSI using SVPWM. In another approach, the authors proposed a nonlinear dynamic model of a Solid oxide FC in transient condition [2].

In this paper a dynamic relationship among voltage, Ohmic loss, activation loss of FC is derived and then used for the simulation. The FC voltage is highly dropped when current is suddenly changed. Furthermore, the polarization curve is directed towards an optimum operating point by manipulating the process conditions. In order to change process parameters such as temperature, anode and cathode pressures of the fuel cell, a new controller is proposed based on interpolation method. When current of the FC is increased, an optimum setting of temperature (or anode and cathode pressure) is derived by an interpolation method to avoid a huge voltage drop. The data used for interpolation are extracted from experimental test.

A Z-Source inverter has been recently designed to convert the power with two capabilities of Buck and Boost. Currently, a VSI is used in FC [3]. This is accompanied with some disadvantages as listed below:

1. An extra DC-DC boost is needed which increases the cost and reduces the efficiency.
2. The lower and upper devices of each phase leg cannot be simultaneously switched on. This reduces the reliability of the inverters.
3. Due to implementation of dead time during the switching of devices, a distortion of output current will be inevitable.

To cope with these disadvantages, a ZSI is proposed in using the FC model for transforming the power. In order to compensate the voltage drop of fuel cell the capacitor voltage of the Z-network is controlled using the state space averaging method to stabilize the AC output voltage of the ZSI. Simulation results are presented using the proposed control strategy and design details are provided in the paper.

2. Z-Source Inverter

2.1. Configuration and operation of ZSI

Fig. 1 shows the general ZSI structure consisting of inductors L_1, L_2 and capacitors C_1, C_2 connected in X shape coupling the inverter to the DC voltage source. The ZSI can produce a desired AC voltage regardless of DC source voltage. The general inverter has six active voltage vectors and one zero voltage vector. However, the three-phase ZSI has one extra zero voltage vector, when the load terminals are shorted through both the upper and lower switching devices of any phase legs.

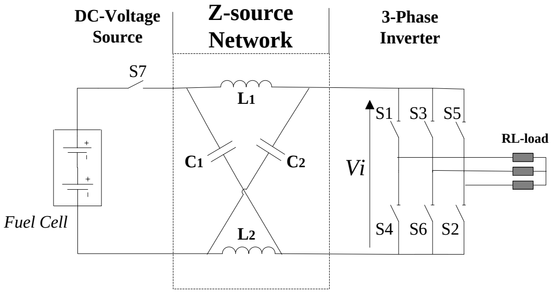
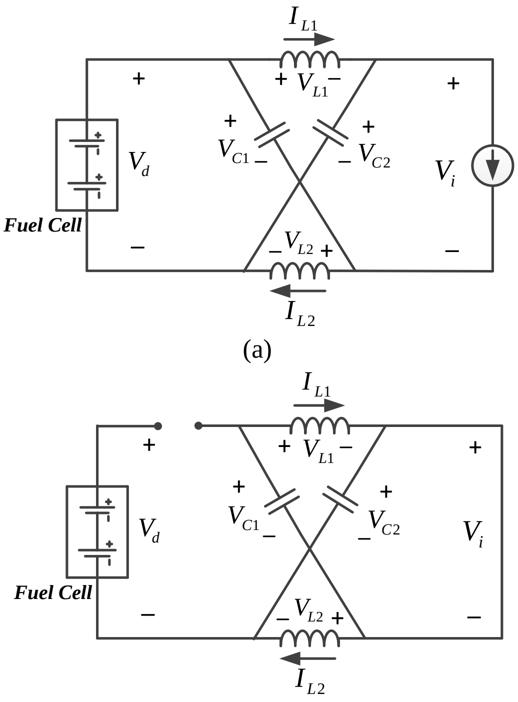


Fig. 1. General configuration of Z-source inverter for fuel cell application

The ZSI has three operation modes: normal mode, zero-state mode, and shoot-through mode. In normal mode and zero-state mode, the ZSI operates under the traditional

PWM (Fig. 2a). In the shoot-through mode, the load terminals are shorted in both the upper and lower switching devices of any phase legs (Fig. 2b). The DC capacitor voltage can be boosted to the desired value, and the shoot-through state is forbidden in the traditional inverter. To strengthen the DC voltage link, a shoot through is used. When duty cycle of shoot-through is controlled, the required output voltage is achieved.



(a)

(b)

Fig. 2. ZSI equivalent circuits in (a) one of the eight nonshoot-through switching states and (b) shoot-through zero state.

Table 1 shows fifteen different states of switching for ZSI. In addition to the usual six active and two zero states in the classic voltage source inverter, extra 7 shoot through states are added. These include a short connection of single-phase terminals (E1 to E3 states) and/or 2-phase terminals (E4 to E6) or (E7 state).

The capacitor voltage is given by below equation [4].

$$V_C = \frac{T_s - T_{sh}}{T_s - 2T_{sh}} V_{dc} = \frac{1 - M_{sh}}{1 - 2M_{sh}} V_{dc} \qquad (1)$$

where $M_{sh} = \frac{T_{sh}}{T_s}$ is a modulation index for T_{sh}.

The stress voltage of the switching device is expressed in terms of M_{sh}.

$$V_i = \frac{1}{T_s - 2T_{sh}} V_{dc} = \frac{1}{1 - 2M_{sh}} V_{dc} \qquad (2)$$

The ratios between the capacitor voltage and stress voltage with DC input voltage versus M_{sh} have been plotted in Fig. 3. In this Fig., as M_{sh} increases from 0 to 0.5, the DC capacitor voltage is boosted, and the voltage stress across the switching device is higher than the capacitor voltage. As M_{sh} approached to 0.5, both the capacitor voltage and stress voltage increases toward infinity. The capacitor voltage can be boosted several times larger than the DC input voltage by controlling the shoot-through time without an additional DC boost converter. This is a unique feature of ZSI.

Table 1
States of switching of z-source inverter.

State (Output Voltage)	S1	S4	S3	S6	S5	S2
Active {100} (finite)	1	0	0	1	0	1
Active {110} (finite)	1	0	1	0	0	1
Active {010} (finite)	0	1	1	0	0	1
Active {011} (finite)	0	1	1	0	1	0
Active {001} (finite)	0	1	0	1	1	0
Active {101} (finite)	1	0	0	1	1	0
Null {000} (0V)	0	1	0	1	0	1
Null {111} (0V)	1	0	1	0	1	0
Shout-Through E1 (0V)	1	1	S3	!S3	S5	!S5
Shout-Through E2 (0V)	S1	!S1	1	1	S5	!S5
Shout-Through E3 (0V)	S1	!S1	S3	!S3	1	1
Shout-Through E4 (0V)	1	1	1	1	S5	!S5
Shout-Through E5 (0V)	S1	!S1	1	1	1	1
Shout-Through E6 (0V)	1	1	S3	!S3	1	1
Shout-Through E7 (0V)	1	1	1	1	1	1

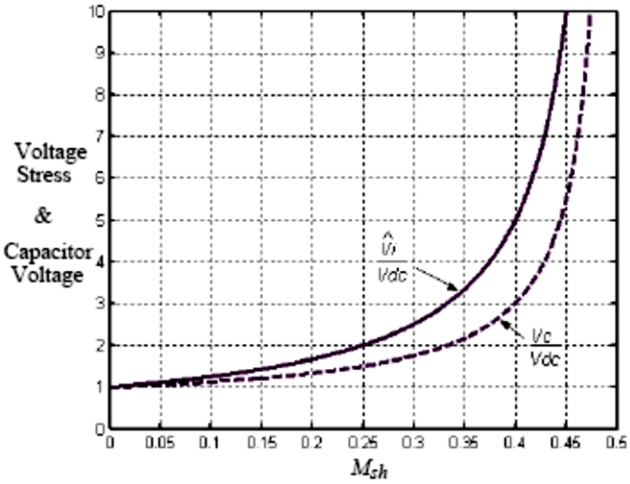


Fig. 3. capacitor voltage and stress voltage according to M_{sh}

2.2. *Control of ZSI based on state space averaging method*

Transfer function of the ZSI is calculated below [5]. The capacitor output voltage after the Z-Network is:

$$\hat{v}_C(s) = \left[\frac{\frac{D'.L}{Z_l}s + D'.(D'-D)}{LCs^2 + \frac{2D'L}{Z_l}s + (D-D')^2}\right].\hat{v}_{dc}(s) + \left[\frac{\left(-2I_L + \frac{2V_C}{R_l} - \frac{V_{dC}}{R_l}\right).Ls + (D'-D).(2V_C - V_{dc})}{LCs^2 + \frac{2D'L}{Z_l}s + (D-D')^2}\right].\hat{d}(s) \tag{3}$$

Where $I_{L1}, I_{L2}, V_{C1}, V_{C2}, V_{dc}$ are DC steady state values and $I_{L1} = I_{L2} = I_L$, $V_{C1} = V_{C2} = V_C$ because of the symmetry of the Z-Network. $Z_l(s) = R_l + sL_l$ is the output load. *D* is the shoot-through duty ratio and the duty ratio of switch S_7 is *D'= 1 – D*. the switching function dependent to the time D(t) is applied to expression the state of the switch, that d(s) is its Laplase.

$G_{Vdc}(s) = \left.\frac{\hat{v}_C(s)}{\hat{v}_{dc}(s)}\right|_{\hat{d}(s)=0}$ is the line to output (capacitor voltage) transfer function:

$$\mathrm{G_{Vdc}(s)} = \frac{[\mathrm{D'(D'-D)L_l + D'L}].\mathrm{s} + \mathrm{D'.(D'-D).R_l}}{\mathrm{L_lLCs^3 + R_lLCs^2 + [2D'L + L_l(D-D')^2].s + R_l(D-D')^2}} \tag{4}$$

$G_{vd}(s) = \left.\frac{\hat{v}_C(s)}{\hat{d}(s)}\right|_{\hat{v}_{dc}(s)=0}$ is the control to output transfer function:

$$G_{vd}(s) = \frac{K_3.s^2 + K_2.s + K_1}{L_lLCs^3 + R_lLCs^2 + [2D'L + L_l(D-D')^2].s + R_l(D-D')^2} \tag{5}$$

With following coefficient:

$$\mathrm{K_3} = \left(-2\mathrm{L_l} + \frac{2\mathrm{V_C} - \mathrm{V_{dc}}}{\mathrm{R_l}}\right).\mathrm{LL_l}$$
$$\mathrm{K_2} = -2\mathrm{R_lL.I_l} + (2\mathrm{V_C} - \mathrm{V_{dc}})\mathrm{L} + (2\mathrm{V_C} - \mathrm{V_{dc}})(\mathrm{D} - \mathrm{D'})\mathrm{L_l}$$
$$\mathrm{K_1} = (\mathrm{D} - \mathrm{D'}).(2\mathrm{V_C} - \mathrm{V_{dc}}).\mathrm{R_l}$$

On the basis of above equation and by the use of PID controller, block diagram shown in Fig. 4 was designed in MATLAB®, that by taking feedback from the capacitor voltage it can reduce the effects of DC input voltage change (that is the same the fuel cell output voltage). Reference capacitor voltage is chosen in accordance with the needed output and boost gain of the ZSI. In fact based on the ZSI operation (equation 1, 2) control of capacitor voltage of the Z-network (V_c) is equal to control of input voltage of the inverter (V_i) and as a result it is equal to AC output of the ZSI.

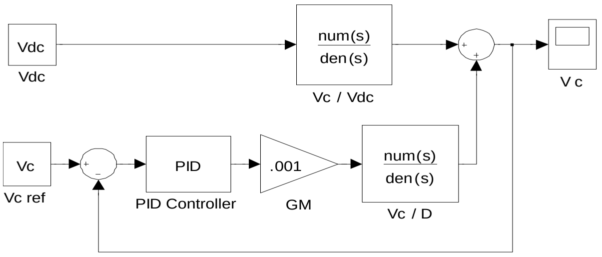


Fig. 4. Block diagram for close loop model based on state space averaging

3. Modelling of PEMFC

Fuel cell voltage is explained as three phrases: thermodynamic voltage, activated over voltage and ohmic over voltage. So that, standard voltage of PEM Fuel Cell (E) is equated with 1.299. Because of unreturnable losses, the real voltage of cell is dropping than to its balance point. In a fuel cell, some sources are causing some unreturnable losses. There are three kinds of Voltage drop (Loss) in the polarization curves such as activation loss, ohmic loss and concentration loss. Concentration loss is ignored because fuel cell is operating in the activation and ohmic loss region. Fundamentally, voltage of a stack can be stated by the following equation:

$$V_{STACK} = N.V_{FC} \tag{6}$$

$$V_{FC} = V_{Cell\ reversible} - V_{act} - V_{ohmic} \tag{7}$$

Where $V_{Cell\ reversible}$ is a thermodynamic voltage which represents voltage cell reversible. The Thermodynamic voltage of E is equal to:

$$E = 1.229 - 0.85 \times 10^{-3}(T - 298.15) + 4.308 \times 10^{-5}T(\ln P_{H_2} + \frac{1}{2}\ln P_{O_2}) \tag{8}$$

3.1. Activation voltage loss

In fuel cells, activation voltage loss depends upon the electrochemical reaction speed of reactors on the electrode's surface. For doing the chemical reaction, reactants should pass through certain over potential and amount of energy should be lost in order to reaction of fuel and oxygen in electrodes which is termed as activation losses. The applied relationships for the modelling of activation voltage losses can be represented as below (That is known Tofel's equation):

$$V_{act} = A\,ln\left(\frac{I_{Fc}}{I_o}\right) \quad , \quad A = \frac{RT}{n\alpha F} \tag{9}$$

3.2. Ohmic voltage loss

Simulation and modelling of ohmic loss consist of resistance for electron transfer in bipolar plate and electrodes and also resistance for proton exchange in MEA. Ohmic loss is explained as below:

$$V_{ohmic} = I_{Fc}(R_m + R_C) \tag{10}$$

This is another relation that can be used for ohmic loss calculation:

$$V_{ohmic} = V_{electron} + V_{proton} = I_{Fc}.R_{internal} \qquad (11)$$

Where $V_{electron}$ is the loss for resistances against the electron transfer on bipolar plate and V_{proton} is the loss for resistance against the proton exchange on MEA. Some of key factors in modeling and analysis of a hydrogen fuel cell are as follows:

- The temperature of operation
- Anode pressure
- Cathode pressure
- The load pressure and/or output current

Fig. 5 shows a MATLAB SIMULINK® block diagram of dynamic model of PEM Fuel Cell.

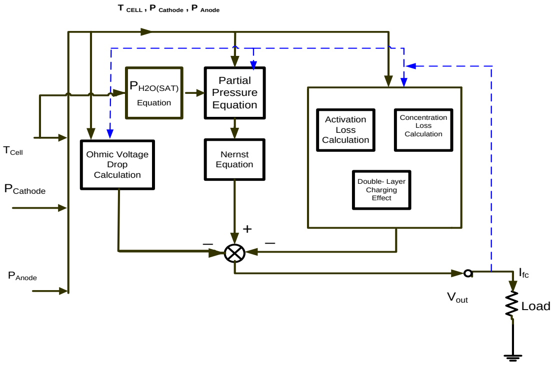


Fig. 5. Simulink Schematic diagram of FC

4. The Proposed Dynamic Model Controller

Variation of current causes a huge voltage change. By changing the process parameters, the polarization curve can be moved towards an optimum operating point. The novel control algorithm is based on a look up table (Fig. 6). Current feedback is the input of look up table; therefore the stack temperature (or anode and cathode pressure) will be controlled according to the feedback current. Therefore the optimum polarization curve could be achieved. By developing the control system, the output voltage of fuel cell shows a minimum change therefore the output voltage of the Z-source inverter has a little change. In addition, in the state space averaging method (Fig. 4), the capacitor voltage is controlled by means of PID controller and capacitor voltage feedback in the case of DC input voltage change. The capacitor voltage in a desirable time can reach itself to the reference amount and at the end the output voltage can stay at a desired amount.

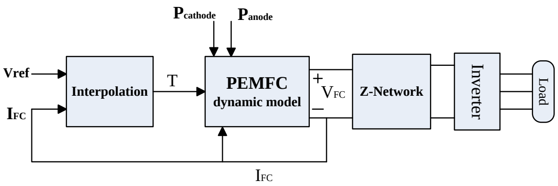


Fig. 6. Block diagram of the proposed dynamic model Controller.

In this model, a program with m-file in MATLAB® is written and it is used by Embedded Function block in Simulink. This program operates with interpolation among these curves and linearizing among the data as it is described below. These data have been experimentally obtained (Fig. 7).

Reference voltage and feedback current, taken from fuel cell output, are the block inputs. The output of this program is the desired temperature for the proposed dynamic model of PEMFC, that is led to produce the voltage accommodated to reference voltage. With the change in output current, for instance the increase (or decrease) of input current, if the temperature of the cell is constant (T_i), its voltage will be dropped on T_i curve. In order to avoid the voltage change, the temperature of fuel cell should be increased (or decreased) in a limited current between the minimum and maximum temperature of the fuel cell. Therefore in accordance with the fix reference voltage and a changed current, the required temperature of the cell is interpolated among the two neighbor curves. This temperature is given to the PEMFC dynamic model in order to produce the voltage accommodated to the reference voltage.

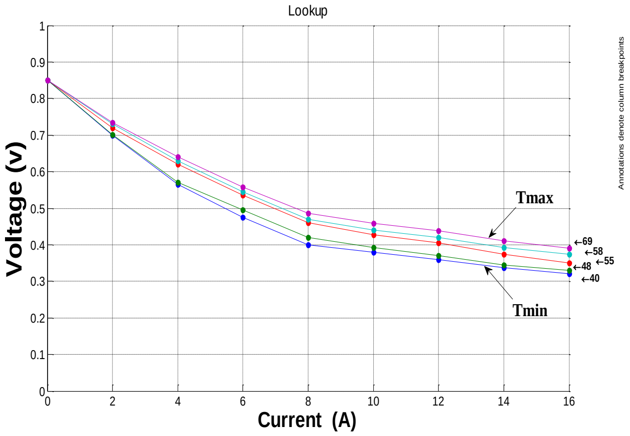


Fig. 7. Lookup table. Operation of the cell in various temperatures (experimental data)

Whereas increase (or decrease) of current reaches to the boundary V-I curves of temperature domain, i.e. the V-I curve with the maximum (or minimum) temperature, it has a voltage drop (or increase) with a constant temperature T_{max} (or T_{min}) compulsorily.

5. Simulation Results

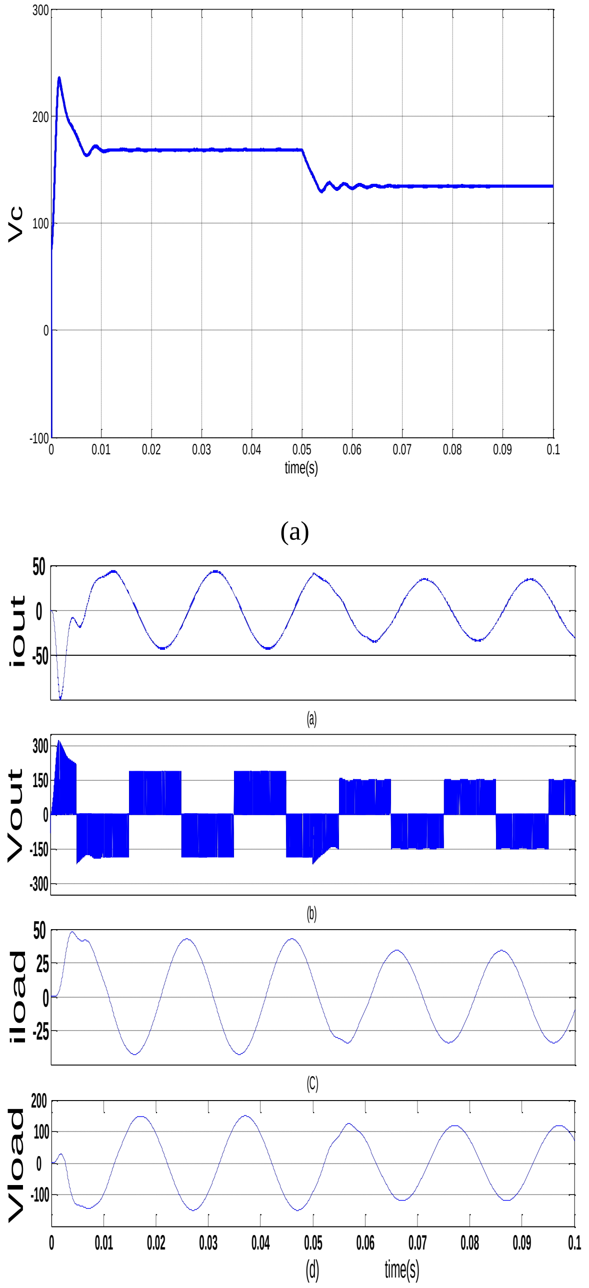
MATLAB/SIMULINK® is chosen for computer simulations. Parameters used for the simulation are shown in Table 2. Three phase R-L load is used as the AC load. The switching frequency of the three phase inverter is 10 KHz .

Table II.
Parameters used for simulation

Value	C_1= C_2= C	L_1= L_2= L	R_L	L_L	f_s	D
Parameter	160 μF	300 μH	12 Ω	0.1 mH	10 kHz	0.3

Fig. 8 shows the simulation results by switching circuit model without controlling the capacitor voltages. During 20% DC input voltage drop it can be seen that the capacitor voltage decreases from 168 V to 135 V and also AC output voltage and current change.

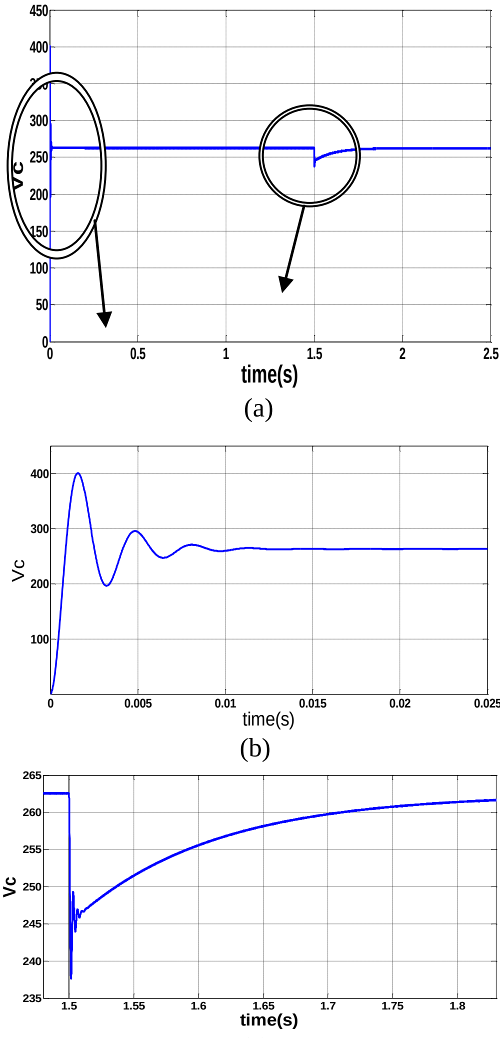
Fig. 9(b) shows the simulation results for capacitor voltages of the Z network. As shown in the figures, the steady state value of the boosted DC voltage by Z-network is 262.5V, perfectly matching the expected value with the DC gain of 1.75 (shoot-through ratio 0.3). We assume that the output voltage of fuel cell is 150 V. Fig. 9(a,c) shows the transient responses during 20% DC input voltage drop (from 150 V to 120 V). The capacitor voltage can be boosted and maintained to a desired level regardless of DC input voltage drop. The shoot-through time is inversely varied with the difference between the capacitor voltage and input DC voltage.



(a)

(b)

Fig. 8. Simulation results. Transient responses during the 20% dc input voltage drop (t=0.05). (a) Capacitor voltage of the Z-network. (b) Ac output current and voltage.



(a)

(b)

(c)

Fig. 9. Simulation results by averaging model; (a) Transient responses during 20% dc input voltage drop (from 150V to 120V); (b), (c) Detail

Fig. 10 shows the transient responses of the capacitor voltage when the reference capacitor voltage is changed from 262.5 V to 272.5 V. The capacitor voltage is boosted to its reference.

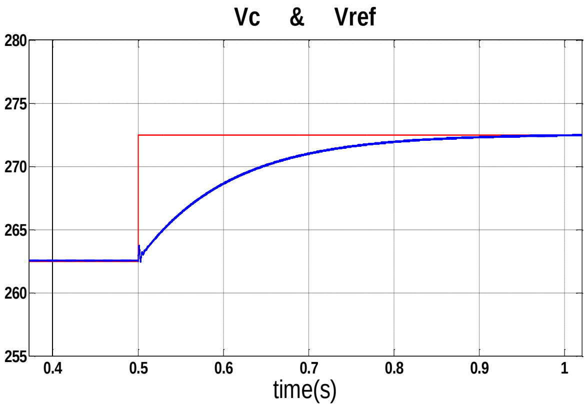


Fig. 10. Simulation results by averaging model when the reference capacitor voltage is changed from 262.5V to 272.5V

6. Conclusion

In this paper, a new strategy was proposed to control both fuel cell output voltage and AC output voltage of the ZSI. A new controller based on the interpolation method was designed. The controller adjusts the fuel cell temperature. An optimum setting of the parameters according to the required output voltage was derived. The effects of the optimum setting on the AC output of Z-source inverter and capacitor voltage have been investigated in this research. The proposed method can achieve good transient responses for variations of the reference capacitor voltage and also during 20% DC input voltage drop. The proposed method was verified by simulation studies.

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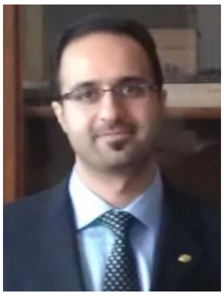
Biographies



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