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A new method for dynamic performance improvement of a hybrid power system by coordination of converter's controller

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ABSTRACT

In this paper, a new strategy for modeling and controlling a hybrid power generation system that contains a fuel cell (FC) and super capacitor (SC) system is proposed. The main drawback of FC systems is its slow dynamic because the FC current slope must be limited in order to prevent fuel starvation problems and to improve its efficiency and lifetime. To overcome this slow dynamic and to improve dynamic performance, a new control strategy is proposed to combine FC system with SC system. The proposed control strategy can be also used for cold starting and different types of FC systems with different dynamics. The control strategy is capable of determining the desired FC power to prolong FC system lifetime and keeps the AC and DC voltages around its nominal value in transient event by supplying propulsion power and recuperating FC energy. The minimum SC system is computed in new method and used to meet the load demand to constraint the DC bus voltage and enhances power regulation under various active and reactive load conditions. Two different case studies are used to obtain the simulation results using MATLAB/SIMULINK to verify the validity of the proposed control strategy.

1. Introduction

Ever increasing electricity consumption and rising public awareness for environmental protection have created increased interest in renewable and alternative power generation systems such as wind, photovoltaic and FC systems. FC systems are one of the most promising energy technologies for the future due to their modularity, high efficiency power generation and environmental friendliness. FC systems are static energy conversion devices that use oxygen and hydrogen to convert chemical energy into electrical energy. FC systems are classified in various types depending on the required electrolyte in each case. For example, the electrolytes in a Proton Exchange Membrane Fuel Cell (PEMFC), a Molten Carbonate Fuel Cell (MCFC) and solid oxide fuel cell (SOFC) are a polymer ion exchange membrane, a combination of alkali carbonates, and a solid metal oxide, respectively [1,2].

The main feature of FC systems is that they can produce reliable power at steady state, but they cannot respond to electrical load transients as fast as desired. This problem is mainly caused by their slow internal dynamic response. Therefore, dynamic FC models are needed to analyze those transient properties and their controllers should be developed to solve or mitigate these problems [3,4].

The FC systems have several other deficiencies such as cold starting and output voltage fluctuation. Due to the low temperature of FC at the beginning of a FC starting, they need more time to produce the desired power. If the FC system is forced to deliver the power to a heavy load during this period or during step load, it could be damaged. To solve these problems, a secondary energy source such as an electrochemical battery or SC system needs to be connected to the FC system to produce power during transient states [5].

A number of literatures have been studied the modeling, control, and performance analysis of FC systems. Wang and Nehrir discussed the modeling, control and fault handling of PEMFC system with real and reactive power demand [6]. Lee and Wang investigated small signal stability analysis of an autonomous hybrid renewable energy. In their paper a simple model of FC system is used [7]. ya Obara proposed a new model of FC system based on experimental research as first order lead lag [8]. Thounthong et al. have improved the FC dynamics using a battery bank as back up to enhance power quality of load demand [9]. El-Sharkh et al. proposed a dynamic electrochemical model for PEM fuel cell power plant in stand-alone residential application [10]. Saha et al. implemented a method for controlling SOFC system in distributed power generation application [11]. Padulles et al. introduced a simulation model of an SOFC power plant. In their model electrochemical and thermal processes were simulated as first order lead lag transfer function [12]. Li et al. controlled SOFC power plant and

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Nomenclature

E_0	ideal standard potential
F	Faraday's constant
I_{fc}	fuel cell current
K_{an}	anode valve constant
K_{H_2}	valve molar constant for hydrogen
K_{H_2O}	valve molar constant for water
K_{O_2}	valve molar constant for oxygen
K_r	constant (= N_0/4F)
M_{H_2}	molecular mass of hydrogen
n_{H_2}	number of hydrogen moles in the anode channel
N_0	number of cells in series in the stack
p_i	partial pressure
$q_{H_2}^{in}$	input fuel flow
$q_{H_2}^{o}$	output fuel flow
$q_{H_2}^{r}$	fuel flow that reacts
R	ohmic loss
R_{H-O}	ratio of hydrogen to oxygen
R	universal gas constant
T	absolute temperature
U	fuel utilization factor
V_{an}	volume of anode
V_{fc}	fuel cell voltage
τ_{H_2}	response time for hydrogen flow
τ_{H_2O}	response time for water flow
τ_{O_2}	response time for oxygen flow

investigated the SOFC dynamic behaviors under a grid-connected condition [13]. Moreover, different previous works have already investigated the active and reactive power flow control of FC systems. The authors in Ref. [14] reported active power flow control of stand-alone PEMFC power plant and controlling AC voltage of inverter for residential application. In their proposed system the FC system is controlled based on traditional methods that are used for the control of active and reactive power output of a synchronous generator. In Ref. [15], a dynamic modeling of PEM fuel cell and an ultra capacitor (UC) system with control of output voltage and active power of inverter for residential application are presented. Uzunoglu and Alam proposed a novel control strategy based on wavelet in hybrid vehicular power system to ensure efficient power flow [16].

Unfortunately, in the control strategy design, the authors did not consider the effect and behavior of FC system utilization factor under disturbance. However in this paper the dynamic model of FC system is modified by considering the effect of utilization factor to operate in optimal value to enhance FC system performance and lifetime. A summary for SOFC system modeling in the recent decade is shown in Table 1.

The main contribution of this study is a novel control strategy for the combination of FC and SC based on modified FC system model which is proposed to overcome FC starvation problem, prolong FC system lifetime and solve the slow dynamics of FC systems in transient events such as step active and reactive load. Also, this modeling and control strategy can show the exact behavior of FC system in transient event and cold starting.

This paper is organized as follows: In Section 2 general principles and dynamic modeling of SOFC are explained. SC model is explained in Section 3. Overall control strategy is investigated in Section 4. Power condition unit model of this system is described in Section 5. Section 6 presents simulation and conclusion is stated in Section 7.

2. General principle and SOFC modeling

SOFC is a static power generation system that produces DC electric power from fuel and oxidant via an electrochemical process. Unlike other fuel cells, the SOFC is in a completely solid state without any liquid components and operating temperatures are about 600–1000 °C. This high temperature allows SOFC system to have internal reforming capability [17,18].

Power generation fuel cell systems include three main parts sections: fuel process unit, power section unit and power condition unit. In this paper a new control strategy based on coordination between these three parts is implemented.

The chemical reactions occurring inside the cell to produce the electricity are:

$$\begin{aligned}&\text{At anode}: \ H_2 + O^{2-} \rightarrow H_2O + 2e^- \\ &\text{At cathode}: \ \left(\frac{1}{2}\right) O_2 + 2e^- \rightarrow O^{2-} \\ &\text{Overall}: \ H_2 + \left(\frac{1}{2}\right) O_2 \rightarrow H_2O\end{aligned} \tag{1}$$

The ratio between reacted fuel flow and input fuel flow of SOFC system (fuel utilization) is expressed as follows:

$$U = \frac{q_{H_2}^{in} - q_{H_2}^{o}}{q_{H_2}^{in}} = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} \tag{2}$$

Every individual gas such as hydrogen or oxygen will be verified separately and the prefect gas equation will be applied to it:

$$P_{H_2} V_{an} = n_{H_2} RT \tag{3}$$

Time derivative of the above expression is:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}} q_{H_2} = \frac{RT}{V_{an}} (q_{H_2}^{in} - q_{H_2}^{o} - q_{H_2}^{r}) \tag{4}$$

The molar output flow of any gas (hydrogen) is proportional to its partial pressure inside the channel:

$$\frac{q_{H_2}^{o}}{P_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{5}$$

Using (4) and (5), the hydrogen partial pressure can be written as follows:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}} (q_{H_2}^{in} - K_{H_2} P_{H_2} - q_{H_2}^{r}) \tag{6}$$

Using (2), (6) can be rewritten as:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}} \left(\frac{q_{H_2}^{r}}{U} - K_{H} P_{H_2} - q_{H_2}^{r} \right) \tag{7}$$

With defining:

$$\tau_{H_2} = \frac{\nu_{an}}{RTK_{H_2}} \tag{8}$$

Taking Laplace transform from (7), the hydrogen partial pressure will be:

$$P_{H_2} = \frac{1/K_{H_2}}{1 + s\tau_{H_2}} q_{H_2}^{r} \left(\frac{1}{U} - 1 \right) \tag{9}$$

According to basic electrochemical relationships, the reacting molar flow of hydrogen can be calculated as follows:

$$q_{H_2}^{r} = \frac{N_0 I_{fc}^{r}}{2F} = 2K_r I_{fc}^{r} \tag{10}$$

Table 1
summary of SOFC system model.

Authors	Fuel cell model	Year	Contribution	Comments
Ro and Rahman	A constant voltage source minus losses	1998	A two-loop controller maximizes performance of solar system and also satisfies the P, Q requirements	Model does not have any dynamics
Hatziadoniu, Lobo, Pourboghrat and Daneshdoost	A simplified dynamic model is developed by authors	2002	Dynamic performance increases as fuel cell rating increases. Fuel cell can have positive effect on transient stability	Conclusion is for a fuel cell in parallel with a gas turbine connected to an infinite bus
Zhu and Tomsovic	Based on Padulles SOFC model 2	2001	Micro turbine helps load following performance	Fuel cell operates as a constant output power DG
Miao and Klein	Based on Padulles SOFC model	2002	Designed controllers to improve the oscillation damping of the whole system using linearized model	Ignorance of incremental fuel cell output voltage. Average model of PCU
El-Sharkh and Saha et al.	Based on Padulles SOFC model	2004 and 2007	In their proposed system PEMFC system is controlled based on traditional methods that are used for the control of active and reactive power output of a synchronous generator	It uses two proportional-integral controllers separately with FC system to control fuel flow. The two controllers are relative to each other
Onar et al.	Based on Padulles SOFC model	2006	The FC system is modified and integrated with the wind turbine generator, electrolizer and storage model	In design of proposed model the authors did not consider the effect and behavior of FC system utilization factor under disturbance and the proposed model cannot show the exact behavior of FC system
Uzunoglu et al.	Based on Padulles SOFC model	2008	Hybrid power generation	In design of proposed model the authors did not consider the effect and behavior of FC system utilization factor under disturbance and the proposed model cannot show the exact behavior of FC system
Proposed model	Based on Padulles SOFC model	2010	1. In this paper the dynamic model of FC system is modified with considering the effect of utilization factor to operate in optimal value to enhance FC system performance and lifetime 2. Proposed model are investigated and are implemented with combination of SC system	

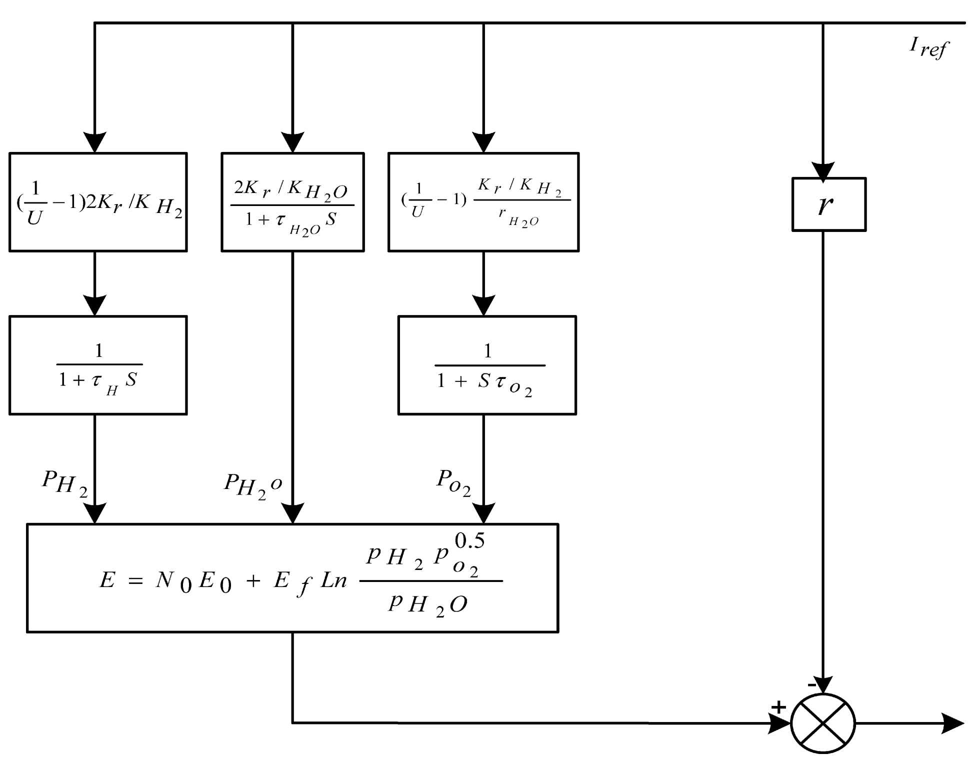

Fig. 1. Dynamic model of SOFC.

Table 2
The parameters of dynamic model of SOFC system.

Parameter	Representation	Value
T	Absolute temperature	1273 K
F	Faradays constant	96,487 C/mol
R	Universal gas constant	8314 J/(kmol K)
E_0	Ideal standard potential	1.18 V
N_0	Number of cells in series in the stack	450
K_r	Constant ($K_r = N_0/4F$)	9.9498×10^{-7} kmol/(S atm)
U_{max}	Maximum fuel utilization	0.9
U_{min}	Minimum fuel utilization	0.7
U_{opt}	Optimal fuel utilization	0.8
K_{H_2}	Hydrogen valve constant	8.43×10^{-4} kmol/(S atm)
K_{H_2O}	Water valve constant	2.81×10^{-4} kmol/(S atm)
K_{O_2}	Oxygen valve constant	2.52×10^{-3} kmol/(S atm)
τ_{H_2}	Hydrogen time constant	26.1 s
τ_{H_2O}	Water time constant	78.3 s
τ_{O_2}	Oxygen time constant	2.91 s
R	Ohmic loss	0.126 Ω
T_e	Electrical response time	0.8 s
T_f	Fuel processor response time	5 s
r_{H-O}	Ratio of hydrogen to oxygen	1.145 s
N_s	Number of stacks	1

Using Nernst equation and ohms law the stack output voltage can be written as follow:

$$V = N_0 \left(E_0 + \frac{RT}{2F} \left[\ln \left(\frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}} \right) \right] \right) - rI_{fc}^{r} \qquad (11)$$

Fig. 1 illustrates the SOFC dynamic model derived base on the above equation. The parameters used in this model are derived from [17]. The SOFC system model parameters used in this paper are shown in Table 2.

3. Modeling of SC system

Energy storage systems such as SC and battery bank play a significant role to effectively supply the insufficient energy of power generation subsystems in hybrid power generation systems. The fact that SC systems can provide high power during positive step load and cold start and can accept and sustain high power during negative step load makes them ideally suited for hybrid power generation. The main features of SC systems are that they demonstrate excellent life cycle and also have a high cycle efficiency compared with chemical batteries.

The model of a SC unit consists of a capacitance (C), an equivalent series resistance (ESR) representing the charging and discharging resistance and an equivalent parallel resistance (EPR) representing the self-discharging losses. The classical equivalent circuit of SC system is also similar to the battery model as shown in Fig. 2 [19,20].

Minimum required SC to meet the power mismatch between FC/SC power and maximum step load demand during mode 2 or mode 3 is calculated as follows. These modes are defined in Section 4.2.

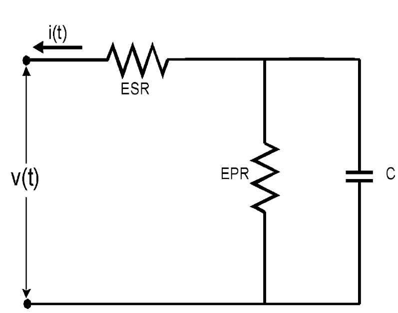

Fig. 2. classical equivalent model of SC system.

The average power and energy drawn from the SC with neglecting power loss can be written as:

$$p_{ave} = \frac{1}{T} \int_{0}^{T} v(t)i(t)dt \quad \text{(mode 2 or 3)}$$
$$W(t) - W_0(t) = \int_{t_0}^{t} cv(t)\frac{dv(t)}{dt}dt = \frac{1}{2}cv^2(t) - \frac{1}{2}cv^2(t_0) \qquad (12)$$

W_0 is the initial energy of SC in mode 2 or mode 3 and can be calculate as:

$$w_{t_0} = \frac{1}{2}cv_{rated}^2 = \frac{1}{2}cv^2(t_0) \qquad (13)$$

The SC should deliver the average power of P_{ave} in time duration of T (during mode 2 or 3) to compensate mismatch power between load and SOFC. In this state, the minimum capacitor which creates the maximum ripple allowed in the system's DC voltage can be calculated:

$$\frac{1}{2}c_{min}(v_{rated/max}^2 - v_{min}^2) = P_{ave}T \qquad (14)$$

$v_{rated/max}$ is the maximum voltage of SC at the starting discharge time (T) and equals to v_{rated} if mode 2 is used to calculate of SC and equals to v_{max} if mode 3 is used to calculate of SC.

v_{min} is the minimum voltage of SC at the end of discharge time (T). This equation can be rewritten as follows:

$$c_{min} = \frac{2P_{ave}T}{(v_{rated/max}^2 - v_{min}^2)} \qquad (15)$$

By considering the power loss in SC, Eq. (14) is changed to:

$$\frac{1}{2}c_{min}(v_{rated}^2 - v_{min}^2) = (P_{ave} - P_{loss})T \qquad (16)$$

And then:

$$c_{min} = \frac{2(P_{ave} - P_{loss})T}{(v_{rated/max}^2 - v_{min}^2)} \qquad (17)$$

c_{min} is calculated in mode 2 and mode 3 and each one that is greater than the other is selected as the required SC system.

4. Overall control strategy

4.1. Modified modeling of SOFC system

Padulles et al. introduced a model for the SOFC power plant [12,17], which is modified for this study. In this paper the model of SOFC is modified to enhance FC system lifetime and to improve SOFC performance. In the studied DG system, the variables should be controlled to enhance power regulation and prolong FC system life time. To achieve this goal the power generation and constraints should be controlled by considering the input reference power to the power electronics interfacing. Utilization factor is one of the most significant variables that may affect the performance of FC system. For safe operation of a SOFC, the consumed fuel in stack needs to be controlled to protect FC system from fuel starvation and permanent damage. Due to this reason the utilization factor has to be kept in its allowable range ($0.7 < u < 0.9$). Overused-fuel condition ($u > 0.9$) and underused-fuel condition ($u < 0.7$) could lead to permanent damage to the cells due to fuel starvation problem and unexpectedly high cell voltages, respectively [13].

To prevent fuel starvation problem (over-use) and also to prevent fuel under-use conditions, the excess ratio of hydrogen fuel flow needs to be adjusted rapidly by increasing and decreasing the mass flow into the FC stack, respectively. These operations are limited by the inertia (dynamic respond) of the actuators. Over-use

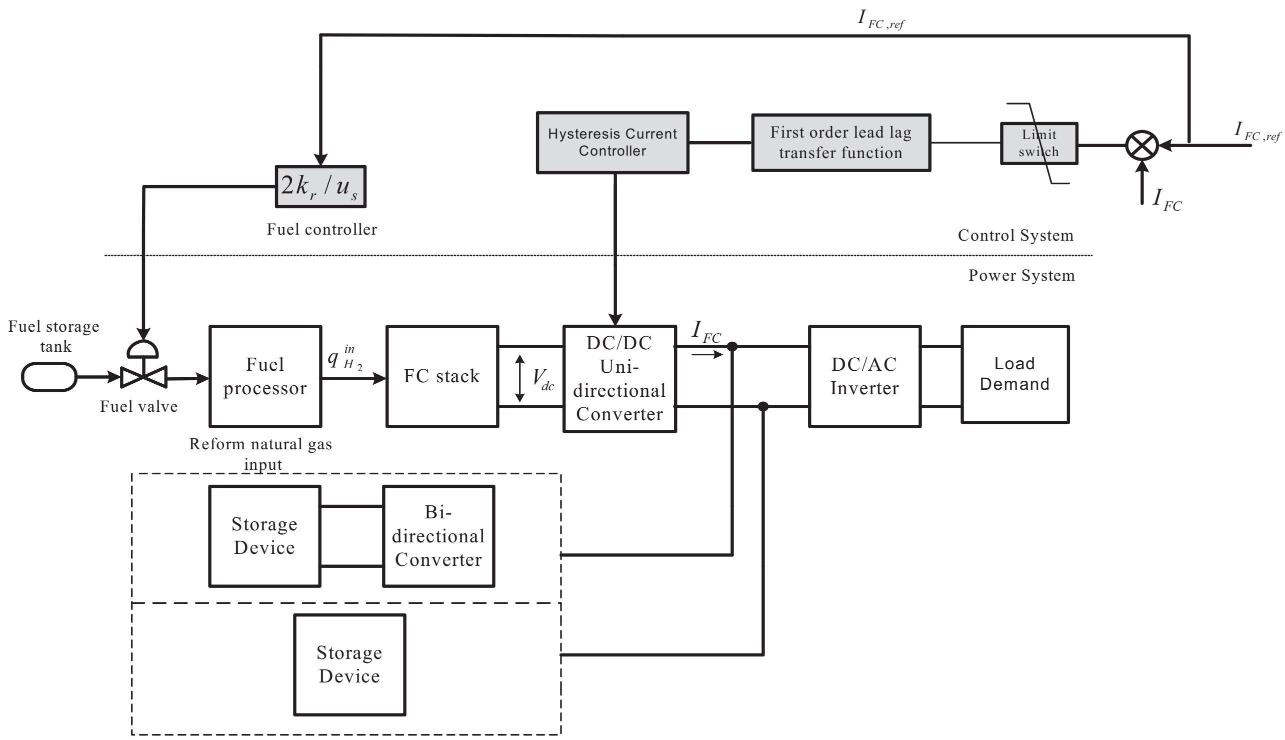

Fig. 3. Overall system, SOFC and their controller model.

and under-use conditions occur especially at fast load changes. This problem can be controlled by limiting the dynamics of load changes.

The input fuel flow of hydrogen is proportional to the stack current and a constant utilization factor in the steady state. Thus, the SOFC stack is operated with a constant steady-state utilization factor by controlling the hydrogen fuel flow input to the stack according to Eq. (10) where, u_s is the optimal utilization factor in steady state. To prolong SOFC system lifetime and to enhance SOFC performance, a new control strategy is proposed. Based on this control strategy, the signal of reference current is directly send to the hydrogen fuel valve and on the other hand with considering the slow dynamic of hydrogen fuel valve, the SOFC system cannot change its power to the desired value in step load and disturbance. So the dynamic of applied signal to the unidirectional converter should correspond to the dynamic of the hydrogen valve. The relationship between a small change of stack current ΔI_{FC} and a small change of hydrogen input ΔH_2 fed to the FC stack can be achieved as Eq. (10). Fig. 3 shows the proposed control strategy for controlling SOFC system.

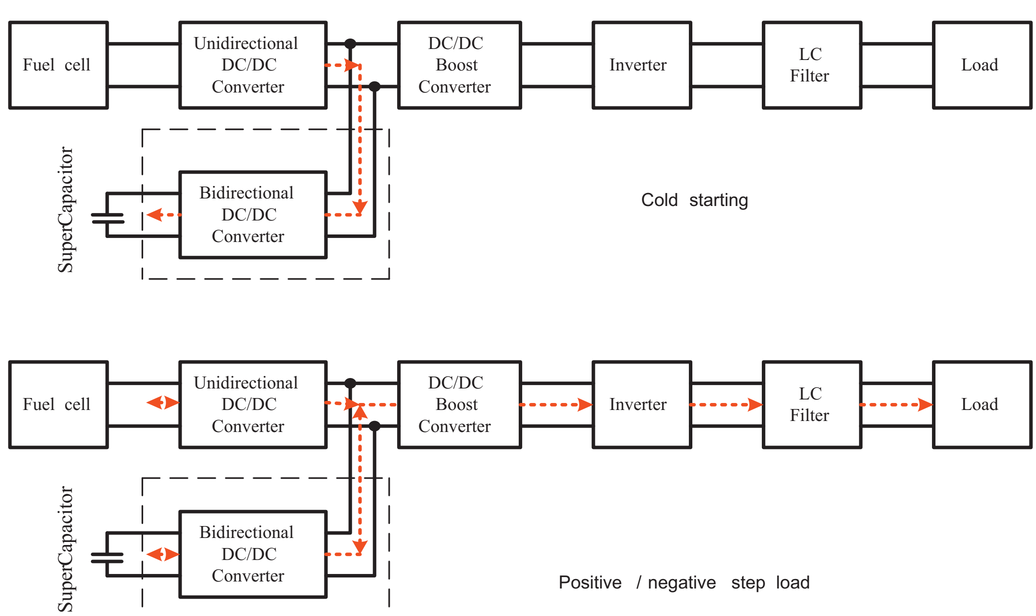

Fig. 4. Block diagram of FC/SC system during cold starting, positive and negative step load. (a) Without bi-directional converter and (b) with bi-directional converter.

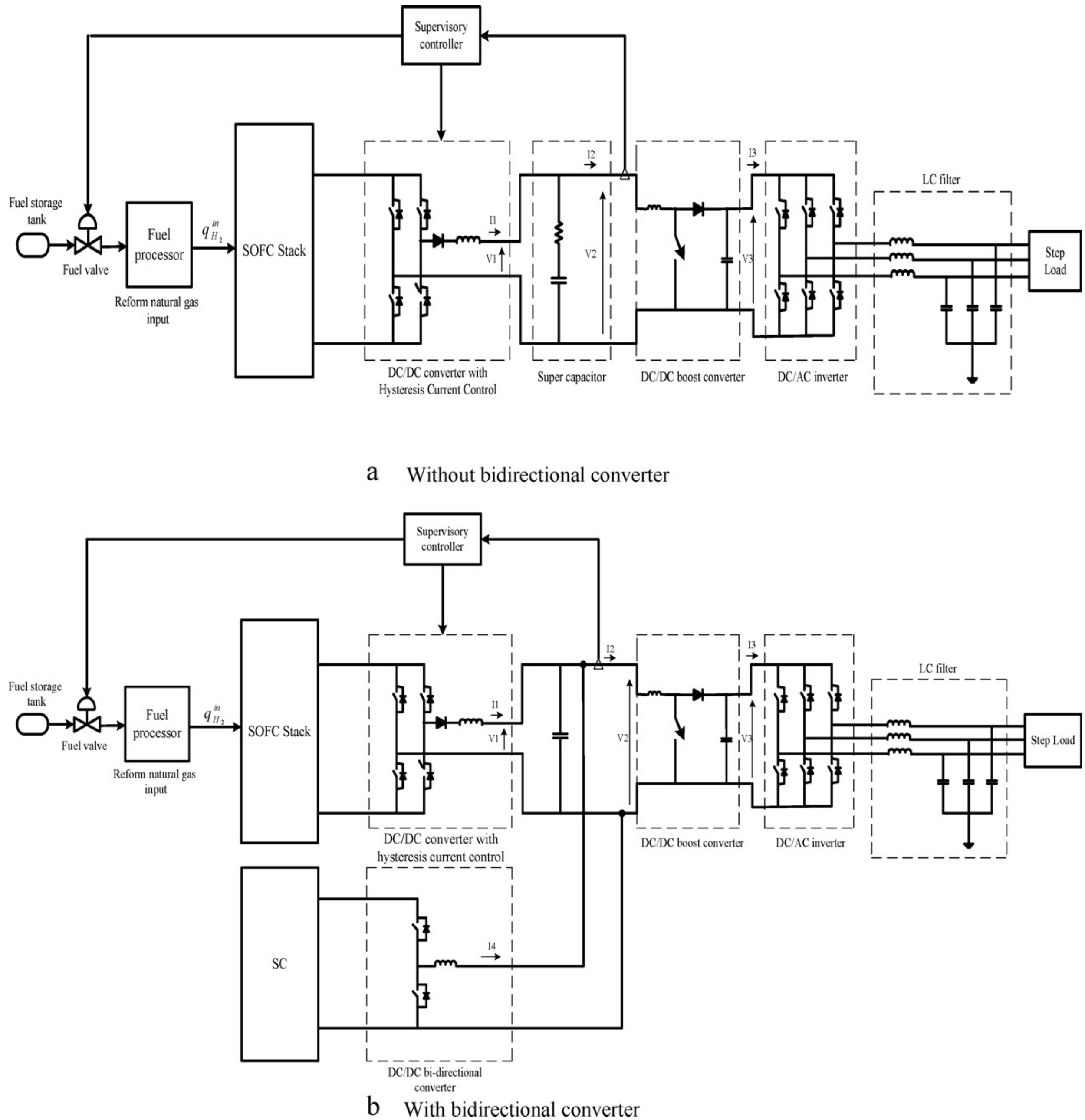

Fig. 5. Block diagram of a SOFC and SC in a distributed generation system without bi-directional converter (a) and with bi-directional converter (b).

4.2. Coordination between SOFC and SC

Fig. 4 shows the two different topologies used in this paper. Due to effect of cold starting and power drawn from FC and/or SC system, the operation and dynamic performance of this system are divided to five different modes as follows:

Mode 1: Due to low temperature of FC system at the beginning of a FC starting, there is no load and FC system needs more time to produce power and charge the SC. At the end of this mode, the SC voltage reaches the final rating value and the hybrid system is ready to deliver the power to load.
Mode 2: The load demand is greater than FC nominal power and the SC system is in full charge state and its voltage is in rating value. In this mode, the power is driven from FC and SC system to load and the SC is being discharged. The minimum required SC system may be calculated due to this mode.
Mode 3: The load demand is greater than FC nominal power and the voltage of SC system is lower than rating value. In this mode, the power is driven from FC and SC system to load and the SC is being discharged. The minimum required SC system may also be calculated due to this mode.
Mode 4: The load demand is lower than FC nominal power and the SC system is in full charged state. In this mode, the FC power follows the load demand.
Mode 5: The load demand is lower than FC nominal power and the SC system is not in full charged state. In this mode, the FC power follows the load demand and the SC system is being charging. The voltage of SC system reaches to rating value at the end of this mode.

In transient state during step load, there is a mismatch between FC power and load demand and the SC system balances the power

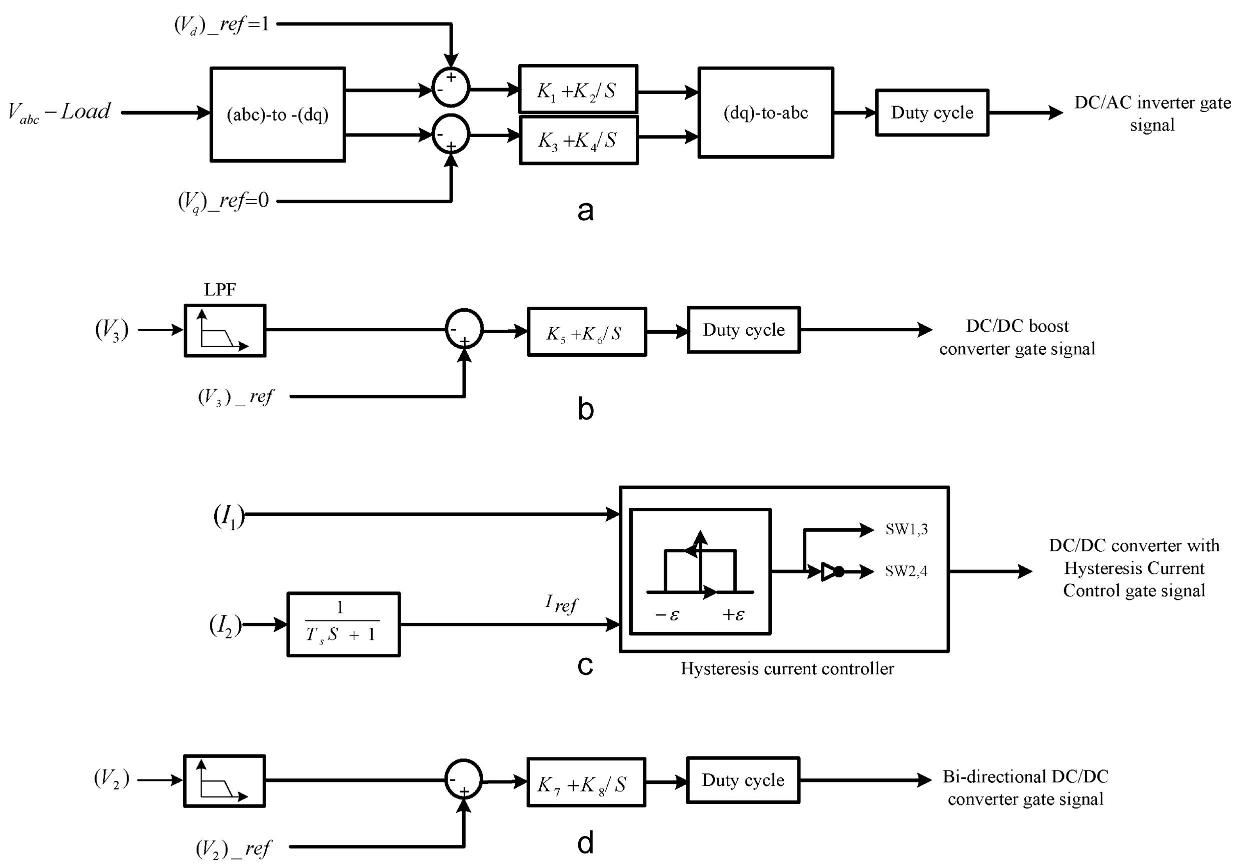

Fig. 6. Block diagram of control system, (a) DC/AC inverter's controller, (b) DC/DC boost converter, (c) D/DC converter with hysteresis current control gate signal, and (d) bi-directional DC/DC converter gate signal.

between them. This transient state takes up to 10 s and DC bus voltage tolerates a voltage variation due to the charging or discharging of the capacitor. This state may be lied in mode 2, 3,4 or 5.

5. Power condition system (PCS)

Due to the slow dynamic of the chemical process, the FC system cannot change its power to the desired value in different conditions such as step load or cold starting and therefore, a PCS which contains the DC/DC and DC/AC converters is used for load sharing between FC and SC system. The proposed control strategy is simulated in two different topologies shown in Fig. 5 to show the effectiveness of the proposed control strategy. The block diagram of the control system is shown in Fig. 6.

In the novel proposed control strategy, to speed the dynamic response of FC system during transient state and prevent fuel starvation, a hysteresis current controller is used instead of other traditional controllers in the DC/DC converter of FC [21]. In this controller, at first, the input current of the DC/DC boost converter is passed through a first order block with time constant of T_s to prevent fuel starvation. Then, the output of this filter is passed through the other block which selects the reference current of the hysteresis current controller (RCHCC).

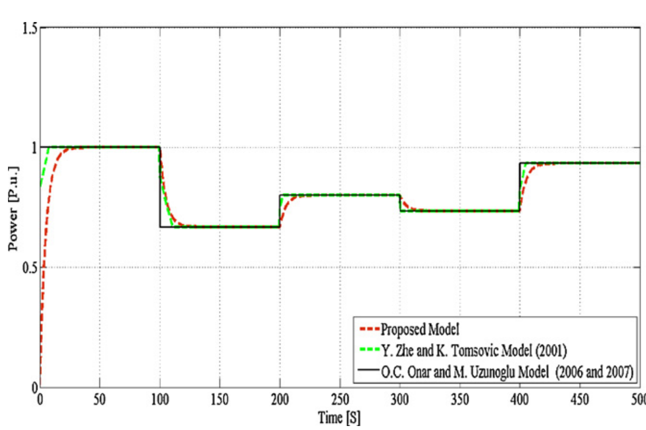

Fig. 7. SOFC output power.

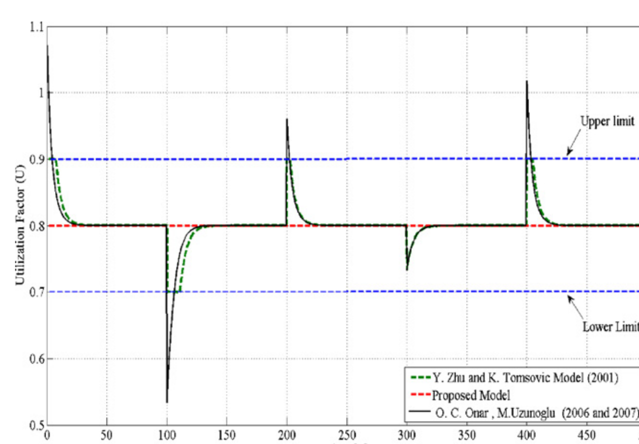

Fig. 8. Dynamic behavior of utilization factor.

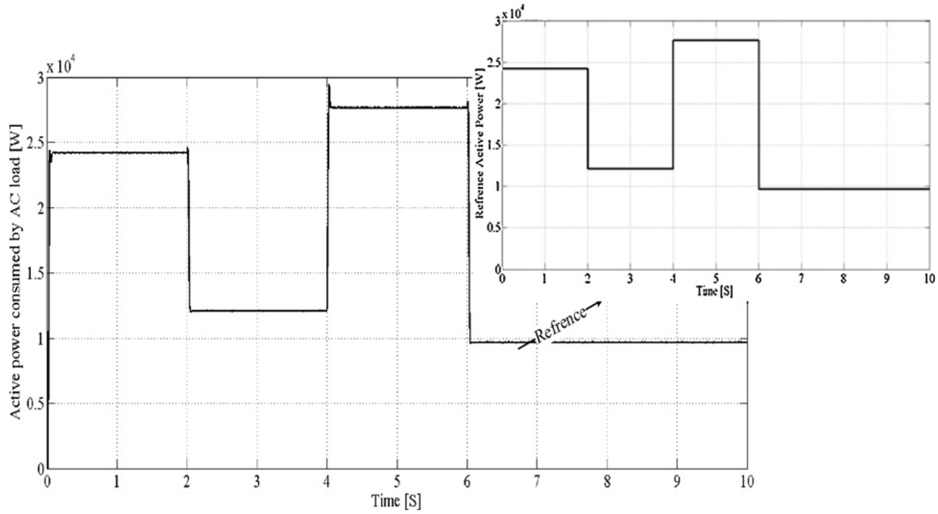

Fig. 9. Active power consumed by hybrid power generation system (case study A).

6. Simulation results

SOFCs may be connected to the SC system in different configurations [22]. In this section, two different configurations for connecting the SOFC system to SC system are presented. These two configurations are used to show the performance of the proposed SOFC system model in different applications. The comparison of these two systems with each other is outside the scope of this study. In the first system, the SOFC is connected to SC system via a unidirectional DC/DC converter and in the second system, the SOFC via a unidirectional converter and SC system via a bi-directional converter are connected to the same DC bus. The voltage of combined SOFC and SC system with the aim of boost DC/DC converter is increased to reach the desired value. Finally, the DC/AC inverter controls the active and reactive power demand of load. With selecting the SC = 4F, the maximum variations of SC system's voltage will be approximately 30 V.

To detailed study of proposed modified modeling of SOFC system precisely, should employ high order mathematical models with nonlinearity. In this section, due to high complexity, nonlinearity, software constraints and long time simulation, simplified model of power electronic interfacing is implemented to show the dynamic behavior and priority of the proposed system. The effects of ripples generated due to the switching of power electronics interfacing are neglected to show the exact dynamic behavior of SOFC system for 500 s. These ripples can be decreased to desired levels by filtering on both the DC and AC sides and by increasing the switching frequency of the power electronics interfacing [7,8,10–13].

In order to investigate the proposed model, this model is compared with previous models with their controller as shown in Fig. 7. Fig. 7 shows that the dynamic response of proposed model is reduced but the SOFC system operates in its optimal value as shown in Fig. 8. These figures show that some proposed model cannot operate in its allowable rang. These models do not have any control strategy for controlling the utilization factor and their utilization factors are out of the allowable range.

In order to investigate all part of proposed model precisely such as voltage variation of power electronics devices, the detail models of power electronics devices and their controller are simulated for short time duration (10 s) in the next sections.

6.1. Case study A: without bi-directional converter (Fig. 5a)

In this case study, the SOFC via DC/DC converter with hysteresis current control is connected to SC system directly. In this section, the modified model of SOFC and correct selection of reference current are used to improve power quality, SOFC system performance and lifetime. The reference current is derived from the input cur-

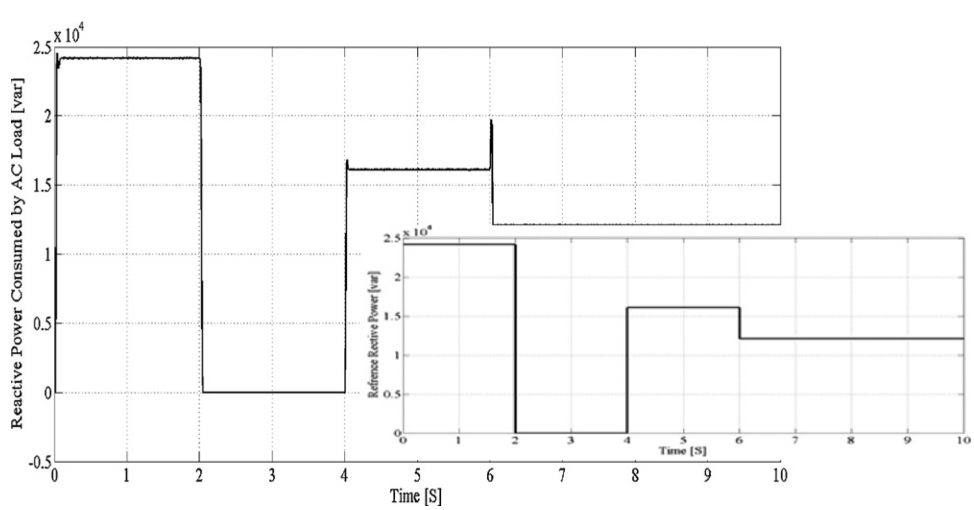

Fig. 10. Reactive power consumed by hybrid power generation system (case study A).

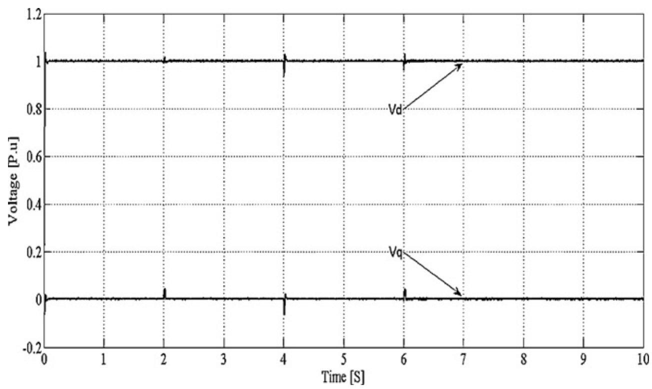

Fig. 11. Variation of load voltage (V_d, V_q) (case study A).

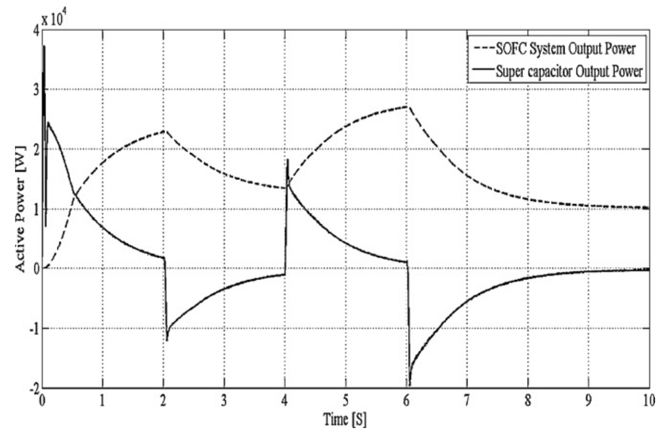

Fig. 12. The active power delivered by SOFC and output power of SC (case study A).

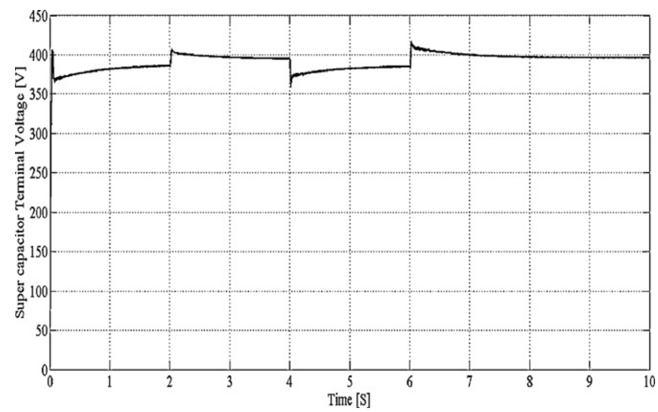

Fig. 13. Variation of SC system terminal voltage (case study A).

rent of DC/DC boost converter and then a supervisory controller produces proper signals for sending to switches of this converter with hystersis current control and hydrogen fuel flow valve. By considering the pervious sections, in this control strategy the SOFC system operates in its optimal value and sets the utilization factor at its optimal value in transient events and disturbance. In transient events and disturbance, the SC system produces deficit power of load demand and gradually the SOFC system satisfies load demand completely.

The output active power and reactive power of the load demand with their references are shown in Figs. 9 and 10, respectively. To supply the active and reactive power of load demand, the voltage of load bus is controlled and fixed at certain value to provide load demand. The variation of load voltage is illustrated in Fig. 11. The produced power of SC and SOFC is shown in Fig. 12. Finally, the voltage variation of SC system is shown in Fig. 13.

6.2. Case study B: with bi-directional converter (Fig. 5b)

In this case study, The SOFC via a DC/DC converter with hysteresis current control and SC system via bi-directional DC/DC converter are connected to the same DC bus. Using a supervisory controller, the proper signals are produced for DC/DC unidirectional converter and for hydrogen fuel valve. Bi-directional DC/DC converter sets the terminal voltage of common DC bus at the specific value. This control has two main advantages, it sets the utilization factor at its optimal value to enhance SOFC system lifetime and

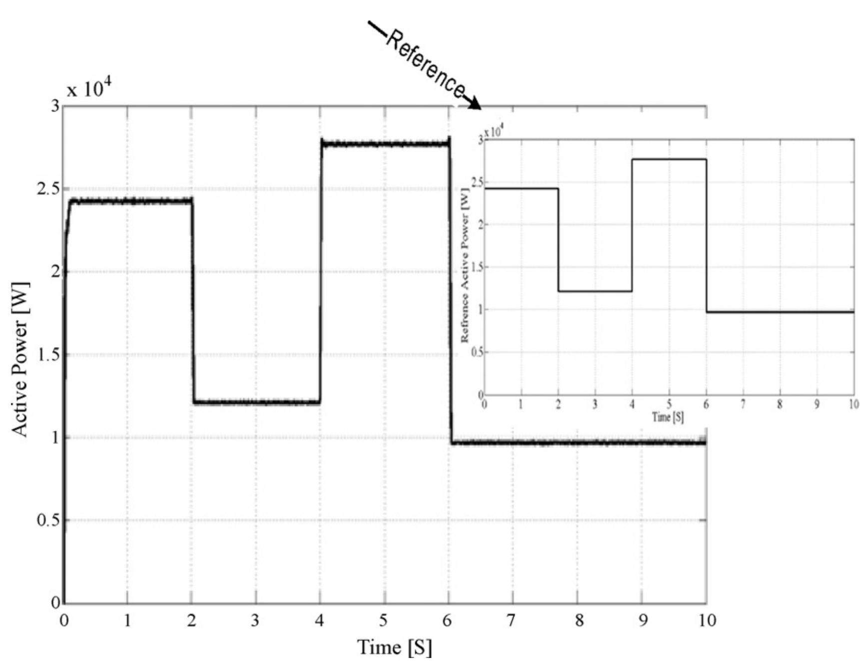

Fig. 14. Active power consumed by hybrid power generation system (case study B).

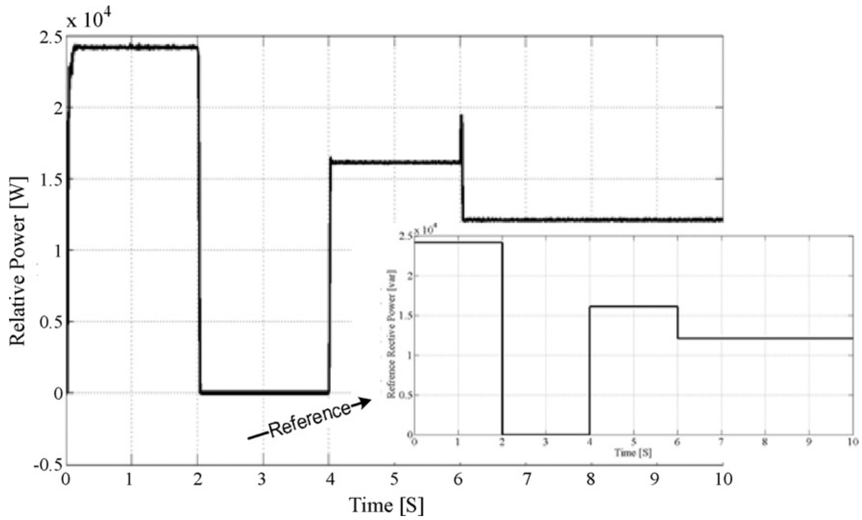

Fig. 15. Reactive power consumed by hybrid power generation system (case study B).

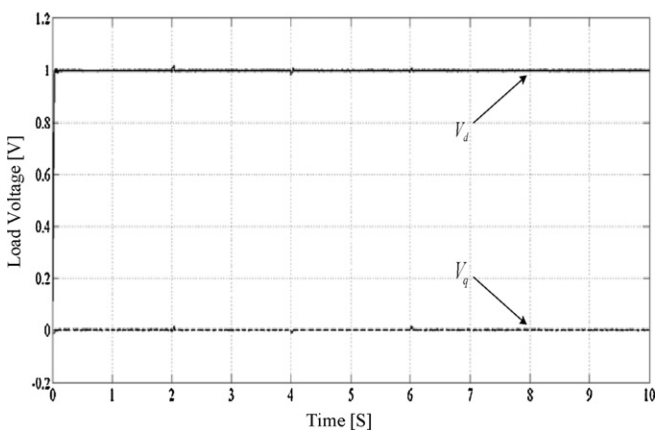

Fig. 16. Variation of load voltage (V_d, V_q) (case study B).

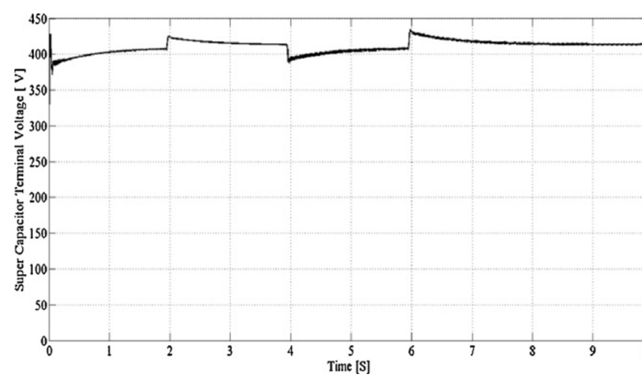

Fig. 18. Variation of SC system's terminal voltage (case study B).

performance and also, it can control combined FC and SC system truly.

The output active power and reactive power of the load demand with their references are shown in Figs. 14 and 15, respectively. To supply the active and the reactive power of load demand, the voltage of load bus is controlled and fixed at certain value to provide load demand. The variation of load voltage is shown in Fig. 16. The produced power of SC and SOFC is shown in Fig. 17. Finally, the voltage variation of SC system is shown in Fig. 18.

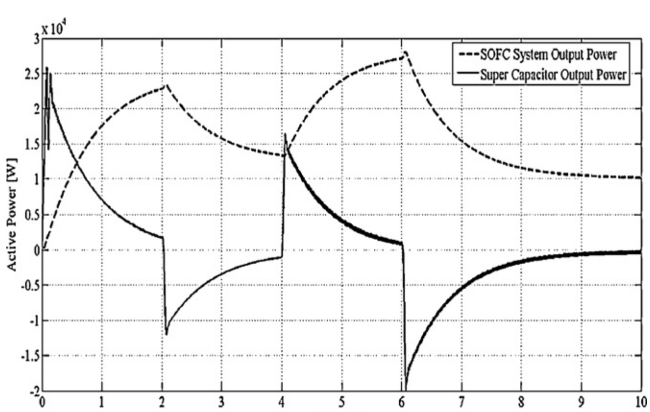

Fig. 17. The active power delivered by SOFC and output power of SC (case study B).

7. Conclusion

In this paper a new control strategy for modeling and controlling of a combined FC/SC system based on modified SOFC system is used to improve active and reactive power regulation in stand-alone application. The proposed model keeps the utilization factor of SOFC system on its optimal value to improve FC system performance and lifetime. Due to the slow dynamic of FC system, SC system is used as secondary system to store the electric power in overproduction and to restore it in underproduction to improve power quality. The proposed control strategy can be used for different types of FC systems with different dynamic respond and cold starting modeling of FC system. Overall hybrid power generation system has been discussed and studied regarding FC system dynamics. All parts of proposed model are investigated in two different models. The step active and reactive load power demands were applied to the system to show the validity of this control strategy and verify system performance.

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