A New Method for Dynamic Control of a Hybrid System Consisting of Fuel Cell and Battery

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Abstract

A new control method was proposed in the current paper for controlling hybrid system consisting of fuel cell and battery. In the proposed control system, a method through which active power of fuel cell is supplied with a relatively high time constant was chosen contributing to enhancement of fuel cell life and maintenance of its terminal in the range of the nominal voltage. Furthermore, ensemble of fuel cell and inverter were used to supply instantaneous reactive power as well; which is possible by using an independent inverter together with fuel cell, and as such ,the setting will respond quickly and perfectly capable to instantaneously supply the reactive power whenever required for the system (voltage reduction or symmetrical 3-phase short circuit). An ensemble consisting of battery and inverter has also been considered for supplying the instantaneous active power, which is connected to the circuit only at early times of change in the power demanded by the system. Its generation power declines after a couple of seconds simultaneously with increase in power of fuel cell until the demanded active power is completely supplied by the fuel cell ensemble.

Keywords

Dynamic Model; Dynamic Control; Hybrid System; Fuel Cell; Battery

Introduction

Fuel cells among the power generation sources without sound pollution feature high efficiency and reliability and low contamination. In addition, their flexible design is responsive to many demands; which makes its extensive application in the future industry. On the other hand, power generation in the fuel cells is a chemical process in which amount of generated active power is controlled by regulating amount of input hydrogen gas and air. This causes a delay in power generation process, and hence, a hybrid power generation system coupled with fuel cell is mostly employed in the dynamic studies aimed at improving dynamic performance of fuel cell and compensating the delayed performance. A battery and inverter together with fuel cell have been used in the present paper to improve performance of fuel cell. Battery and inverter will generate instantaneous power (through controlling the frequency and voltage) in the initial moments of power variation in the system, and then the generated active power of fuel cell will increase using an appropriate control system and with a suitable time constant while the active power generation of battery and inverter will proportionally decrease. The whole demanded active power will be supplied by the fuel cell after a couple of seconds. This controlling method leads to proper power generation performance of fuel cell followed by enhancement of fuel cell life and maintenance of its terminal voltage in the range of nominal voltage. The respective hybrid system also has a very quick dynamic response which can improve the dynamic stability in the networks lacking suitable dynamic performance. Generated reactive power of fuel cell varies with a very low time constant but does not bring about a limitation for the fuel cell because the generated reactive power never causes abrupt changes in the amount of generated power in the fuel cell. This leads to improvement of generation capacity of reactive power compared to the former methods and will promote voltage stability in voltage drop moments or in short-circuits which cause voltage reduction. As such, fuel cell system and its inverter will have the ability to independently generate instantaneous reactive power; which is one of the advantages of the proposed method in comparison with former models which deployed single-inverter system. Additionally, the generated active power of fuel cell is completely governed by controlling its inverter and its variation value is perfectly controlled at any time. In references, a hybrid system consisting of fuel cell, capacitor, battery, and an inverter has been used; power generation is controlled by the inverter and no control is imposed on the active power generated by the fuel cell.

Power Systems Stability

Generally, stability signifies tendency of a power system to have a steady and ideal performance in a point; and is divided into two general categories: Rotor angle stability, the capability of interconnected synchronous machines in a power system to remain in synchronic state with each other and voltage stability, the ability of power system to maintain an acceptable steady state voltage in its all machines either in normal performance conditions or after the occurrence of perturbation.Based on the perturbation intensity, stability is divided into three groups:

1- Steady state stability (very small perturbation)
2- Dynamic stability (small perturbation)
3- Transient stability (very large perturbation)

Dynamic Stability of Power Systems

Ability of system to maintain the new conditions after occurrence of fluctuation caused by a low-amplitude perturbation is referred to as “dynamic stability”. These perturbations might occur due to small changes of charge or generation and can be alleviated through designing an appropriate and stable control system.

Dynamic Model of Fuel Cell

Numerous dynamic models have been extracted and appliedto simulate fuel cell in the power system. In the current paper, a model for fuel cell has been simulated in DIGSILENT software extracted from the simulated models of the reference papers.

The fuel cell (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, more time is required 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 Super Capacitor system need to be connected to the FC system to produce power during transient states.

A number of literatures have studied the modeling, control, and performance of FC systems. Wang and Nehrir discussed the modeling, control and fault handling of PEMFC(Proton Exchange Membrane Fuel Cell) system with active and reactive power demand. Lee and Wang investigated small signal stability analysis of an autonomous hybrid renewable energy. In their paper, a simple model of FC system was used. S. Obara proposed a new model of FC system based on experimental research as first order lead lag and implemented a method to control solid oxide fuel cell (SOFC) system in distributed power generation application. 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. Li et al. controlled SOFC power plant and investigated the SOFC dynamic behaviors under a grid-connected condition. Moreover, different previous works have already investigated the active and reactive power flow control of FC systems.

Unfortunately, in the control strategy design, the effect and behavior of FC system utilization factor under disturbance were neglected. However, in this paper, the dynamic model of FC system has been modified by considering the effect of utilization factor to operate in optimal value to enhance FC system performance and lifetime.

Chemical Reactions in Fuel Cell

As a static power generation system, fuel cell generates DC electrical power via combination of fuel and oxygen in an electrochemical reaction. Fuel supply unit, power section, and power condition unit are three main constituent parts of a fuel cell.

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.

The chemical reactions taking place in fuel cell for power generation are as below:

At anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$

At cathode: $(1/2)O_2 + 2e^- \rightarrow O^{2-}$ (1)

Overall: $H_2 + (1/2)O_2 \rightarrow H_2O$

Fuel consumption is controlled by the ratio of the current reacting fuel and current input fuel of the cell through the following formula:

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

Equation of any ideal gas like hydrogen and oxygen can be independently written as below:

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

By derivation with respect to time from the above relation:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}} q_{H_2} = \frac{RT}{V_{an}}(q_{H_2}^{in} - q_{H_2}^{0} - q_{H_2}^{r}) \tag{4}$$

Output molar of each gas (hydrogen) is proportional to partial pressure inside the canal.

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

Using equations (4) and (5), partial pressure of hydrogen can be written as:

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

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

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}}\left(\frac{q^{r}_{H_2}}{U} - K_H P_{H_2} - q^{r}_{H_2}\right) \tag{7}$$

τH2 is defined as below:

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

Partial pressure of hydrogen is derived by taking Laplace transform from Equation (7) as follows:

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

According to fundamental electrochemical equations, reacting molar current of hydrogen can be calculated via the following relation:

$$q^{r}_{H_2} = \frac{N_0 I^{r}_{fc}}{2F} = 2K_r I^{r}_{fc} \tag{10}$$

Using NERNST equation and Ohm's law, output voltage can be written as:

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

Figure 1 illustrates dynamic model of fuel cell. The parameters and values of fuel cell dynamic model used in the current paper are shown in table 1.

TABLE 1. VALUES AND PARAMETERS OF FUEL CELL CONTROL SYSTEM AND DYNAMINC MODEL

Model	Parameters	Value
K1	I_{base}	1000
K2	2Kr/Uopt	2.74e-6
K3	1/tau_f	0.2
K4	2*K_r	2.33e-6
K5	1/K_H2	1186.24
K6	1/tau_H2	0.0383
K7	1/K_H2O	3558.71
K8	1/tau_H2O	0.0128
K9	1/r_HO	0.8734
K10	K_r	1.16e-6
K11	1/K_O2	396.8254
K12	1/tau_O2	0.3436
K13	R*T/2/F	0.0548
K14	N0	450
K15	$1/V_{base}$	0.001

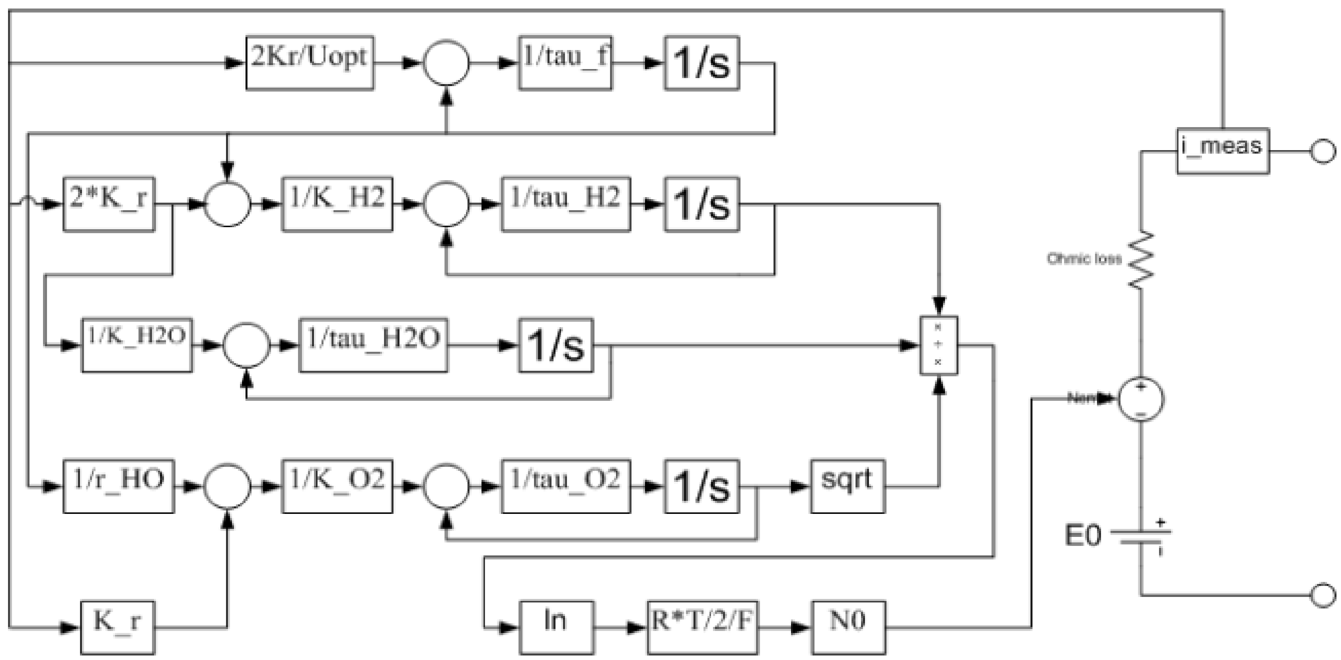

FIG. 1 DYNAMIC MODEL OF THE FUEL CELL UNDER STUDY

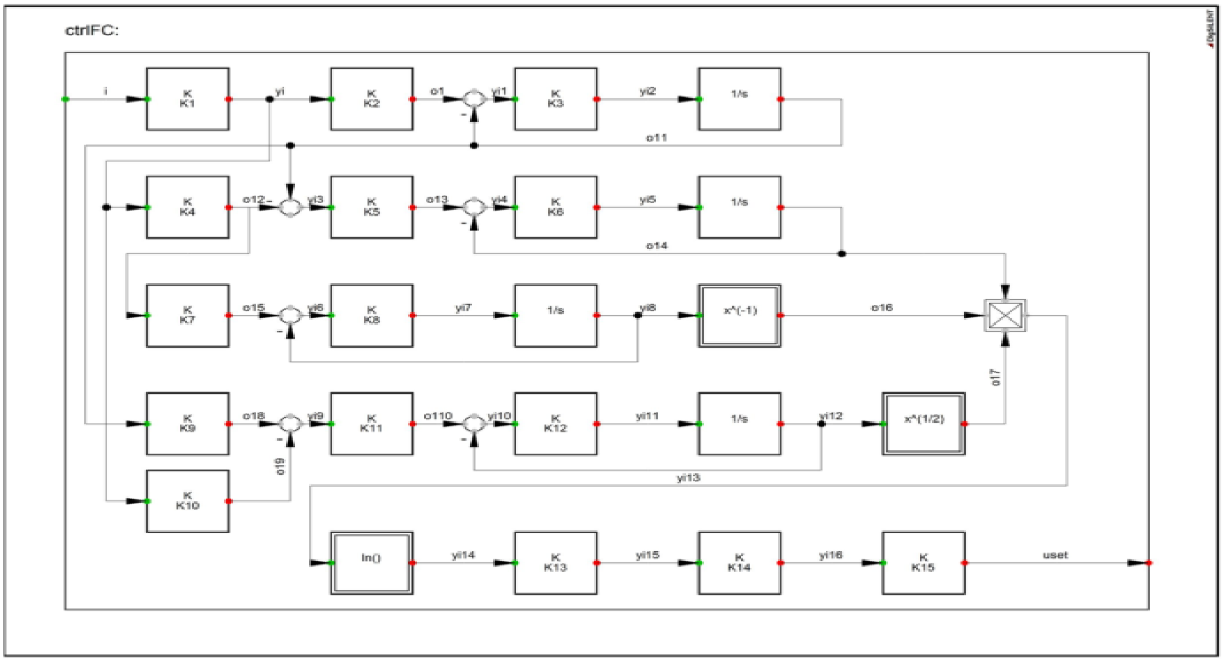

FIG. 2 GENERAL SCHEME OF CONTROL SYSTEM OF THE FUEL CELL

Control and Power System Modeling of the Fuel Cell in DigSilent Software

With further current extracted from the fuel cell, a voltage drop occurs on the fuel cell terminal due to presence of internal resistances. This voltage drop compensated by controlling partial pressure of the fuel causes a dynamic behavior in the fuel cell under load change conditions. This dynamic behavior is modeled with control system of fuel cell whose input and output respectively are intensity of the current extracted from the fuel cell terminal and the signal representing value of additional generated voltage in the dynamic conditions. This signal can be converted into an effective voltage on the output terminal of fuel cell by applying it to a dependent voltage source connected in series. General scheme of the fuel cell control system can be observed in Figure 2.

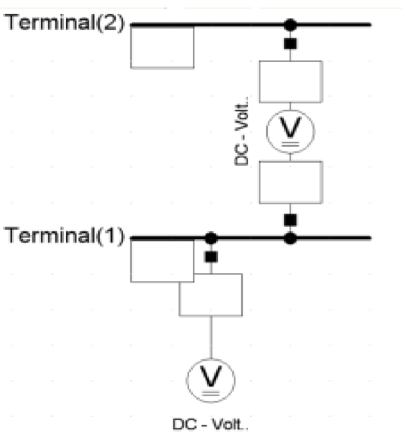

FIG. 3 GENERAL SCHEME OF POWER SYSTEM OF THE FUEL CELL

The modeled fuel cell is composed of two power and control systems. In the power system of fuel cell, standard ideal driving force (E0) was modeled using a DC voltage source and additional generated voltage in dynamic conditions was represented by another voltage source connected in series with the former voltage supply; and internal resistance of sources was modeled by an internal resistance inside the connected voltage source. General scheme of power system of the fuel cell can be observed in Figure 3.

Values of fuel cell control system parameters are listed in table 1.

Block-Frame Diagram of the Fuel Cell in DSL (Digsilent Simulation Language)

Block-frame diagram related to fuel cell for connection between current measurement device and control and power systems of fuel cells is demonstrated in figure 4.

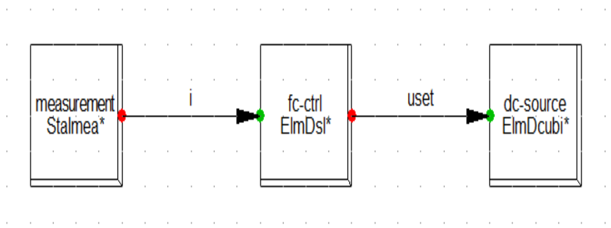

FIG. 4 BLOCK-FRAME DIAGRAM OF FUEL CELL

The Proposed Control Method

DC/AC inverters are used to connect DC power generated in fuel cell to AC-power distribution system;

which enables control of active and reactive power generation. As a result, coefficient of generated power can be adjusted in the case of using converters with switches of mandatory commutation type (e.g. IGBT). Fuel cell is connected to the AC network by a PWM inverter, and similarly, a battery together with another PWM inverter is connected parallel to the fuel cell-inverter ensemble. These two systems together undertake the duty to supply the required power. Battery and inverter ensemble act as the instantaneous power supplier, and in the event of variation in the demanded power, immediately regulate their delivered power proportional to these variations. They keep supplying the power charge if no other supply source is available in the system. Yet, immediately following injection of power supply from another source, this ensemble adjusts its delivered power commensurate with amount of the injected power. Fuel cell and inverter ensemble is used as power generation system which connects to the circuit with a delay. This is possible by applying two inverters, and according to references, the absence of control on the output power of fuel cell does not guarantee a safe productivity of the fuel cell. This delayed performance also contributes to enhancement of fuel cell life, and also, maintenance of DC Bus voltage in the nominal value. The system is capable of abruptly generating reactive power with a short delay parallel to battery and inverter ensemble. The delay is due to the absence of identical working point to supply the reactive power with the battery-inverter ensemble in the transient state; hence, a working point is created for the network in transient states. In single-inverter systems, amount of generated reactive power is less than that of the proposed hybrid system and fuel cell is not used as independent generation source of abrupt reactive power. Additionally, single-inverter systems, due to having less generated reactive power sources than the two-inverter systems, exhibit lower capability to supply reactive power of network in short circuit cases when the voltage drops severely.

Model of Proposed Hybrid System

General scheme of the network under study is illustrated in figure 5. In this network, fuel cell is modeled with an independent DC voltage source and a dependent DC voltage source connected via a DC/DC boost converter to the inverter, and accordingly, its voltage increases to nominal DC Bus voltage value of inverter. This DC voltage is transformed by an inverter into AC voltage and gets connected to AC Bus. As well, parallel to fuel cell ensemble, the battery is also connected to AC Bus using an inverter and the whole setting of fuel cell, battery as hybrid system, and gas turbine feed the load in island network.

Control Method of Fuel Cell Inverter

As mentioned earlier, the demanded active and reactive powers are instantaneously supplied by battery and inverter ensemble in the network under study. The amount of consumed active power load (P_L), the reactive power delivered by battery to the load (Q_b), active power (P_{FC}), and reactive power (Q_{FC}) delivered to inverter-fuel cell are all sent to power measurement

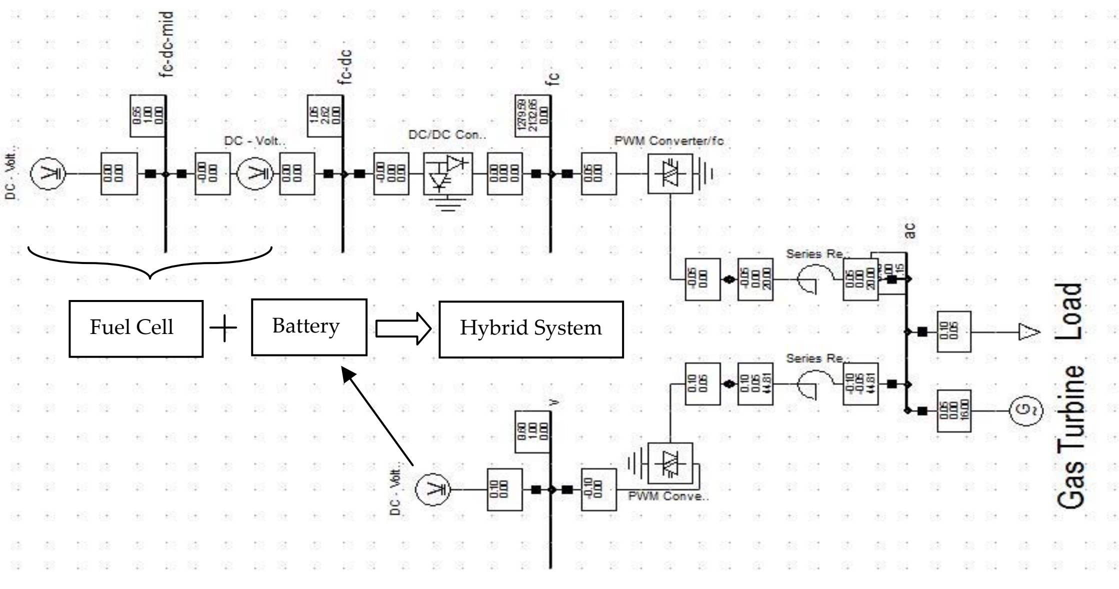

FIG. 5 GENERAL SCHEME OF THE NETWORK UNDER STUDY

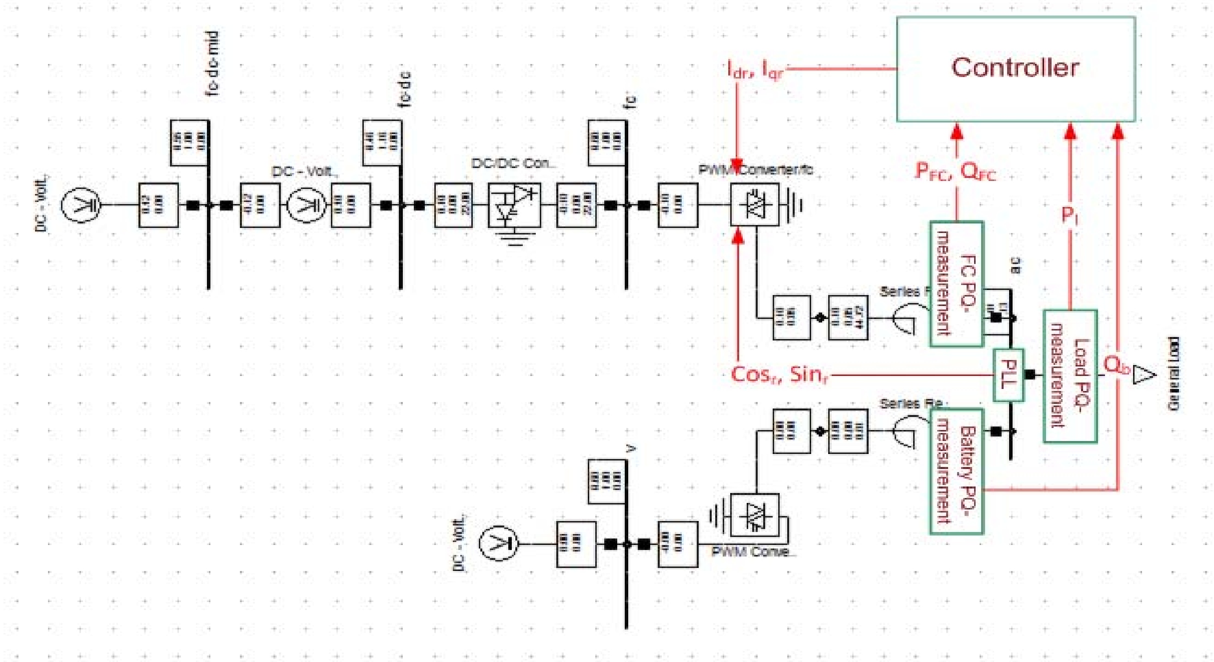

FIG. 6 THE CONTROL SYSTEM USED IN THE HYBRID SYSTEM

by the controller. Consumption load power is then compared with fuel cell inverter delivered power and an error signal is generated and controller determines values of d-axis currents by means of conventional PI controllers proportional to this error signal. After passing through a low-pass filter, this current is delivered to the inverter as reference d-axis current (I_{dr}). Since the variations load might occur in steps, intensity of reference d-axis current (I_{dr}) in the output of PI controller undergoes sudden changes. If this current is directly applied to the inverter, an abrupt DC current will be extracted from the fuel cell which might be unable to support and the terminal might suffer from severe voltage decline disturbing performance of inverter as a consequence. Accordingly, these abrupt changes can be completely eliminated by passing signal of reference d-axis current through a low-pass filter and the current extracted from fuel cell will always decrease or increase with a gentle slope. Besides enhancement of fuel cell life, this causes the DC Bus voltage of fuel cell to permanently remain close to the nominal voltage and inverter will always have a safe performance in this state. The amount of reactive power delivered by battery is also compared with reactive power of inverter-fuel cell and the resulting error signals are transmitted to a conventional PI controller and value of Reference d-axis current (I_{dr}) is determined. This current is given to the inverter as the reference current of q-axis after passing through a low-pass filter with a very small time constant. Selection of reactive power generated by battery as the reference reactive power is due to the fact that increase in reactive power generated by fuel cell reduces the reactive power supplied by the battery, and also, when these two values are equal and reactive power of consumption load are supplied equally, both sources will have greater capacity of reactive power generation compared to the state where one of them supplies the reactive power of consumption load individually. Network frequency and the zero-passing voltage point are given by PLL in the form of two signals (Sin_r, and Cos_r) to the inverter.

Block-Frame Diagram of Control Method in DSL

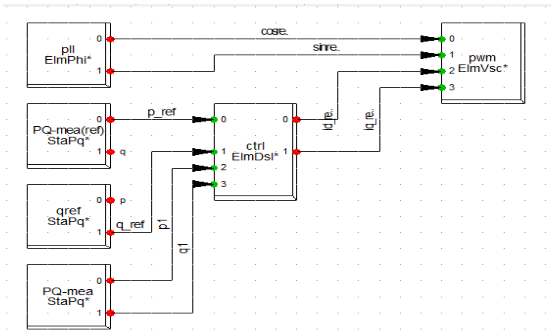

FIG. 7 BLOCK-FRAME DIAGRAM OF CONTROL METHOD IN DSL

The relationship among power measurements, control block, and inverter of the fuel cell is shown by block-frame diagram in Figure 7.

Control System of Fuel Cell Inverter

Active and reactive powers of measurement tools are delivered to control system of fuel cell inverter as input, and reference d and q axes powers are generated. Figure 8 represents this control system.

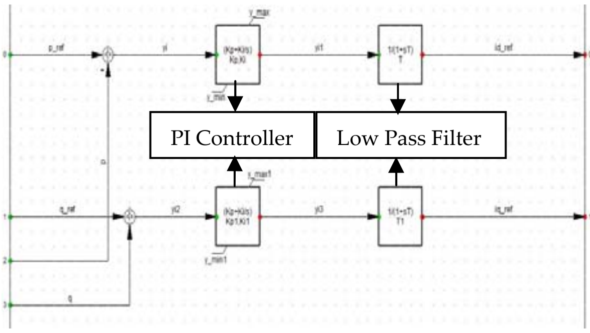

FIG. 8 CONTOL SYSTEM of FUEL CELL INVERTER

Simulation Results

The respective system is simulated by DIGSILENT software, on which RMS simulation studies are applied. The simulation results are subsequently presented.

To check efficiency of the proposed control system, abrupt variations of load active and reactive power in different times were applied according to Table 2. Generated powers of fuel cell and battery were evaluated during these variations in Figures 9 to 11. Results indicate that battery and inverter immediately supply the power changes in the initial instants of variations in the system, and after a couple of seconds, generation power of fuel cell increases slowly and generation power of battery decreases as the former goes up. It must be noted that reactive power delivered by fuel cell is able to vary instantaneously because DC current of fuel cell will not vary for changing the reactive power of fuel cell inverter.

TABLE 2 ABRUPT CHANGES OF ACTIVE AND REACTIVE POWERS OF LOAD

Changes of reactive power	Changes of active power	Time (Second)	Case
50%	75%	40	1
-25%	-50%	80	2
50%	25%	120	3
-80%	-50%	160	4

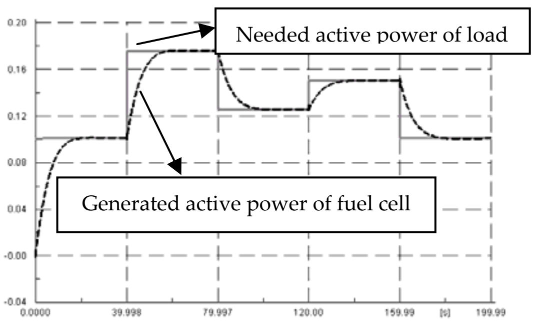

FIG. 9 NEEDED ACTIVE POWER OF LOAD;____GENERATED ACTIVE POWER OF FUEL CELL

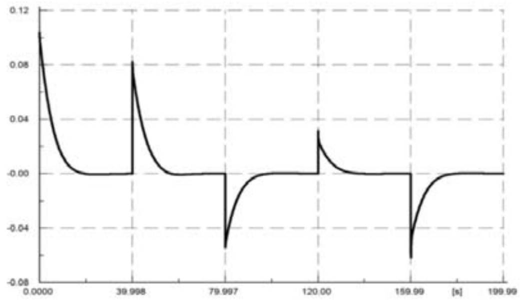

FIG. 10 ACTIVE POWER OF BATTERY

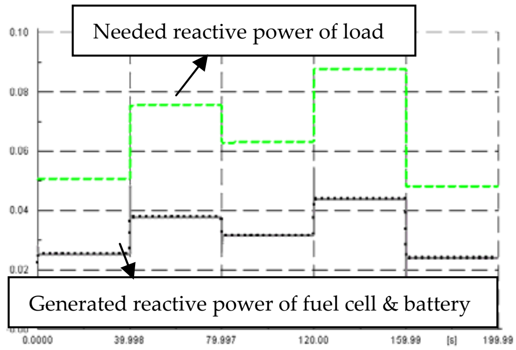

FIG. 11NEEDED REACTIVE POWER OF LOAD

. . . . . GENERATED REACTIVE POWER OF FUEL CELL

_____GENERATED REACTIVE POWER OF BATTERY

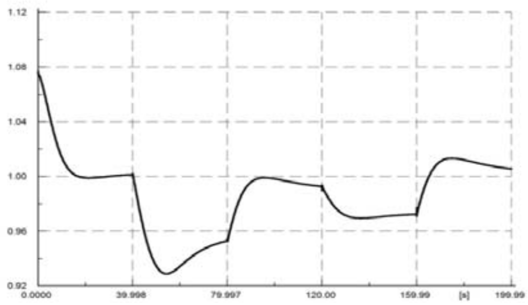

FIG. 12 DC VOLTAGE OF FUEL CELL TERMINAL

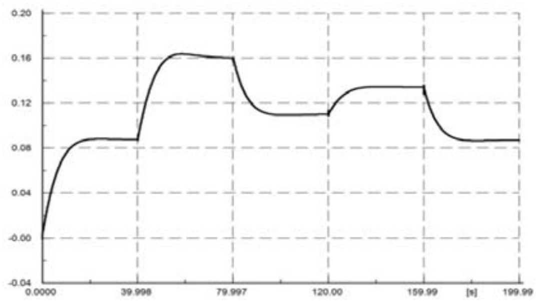

FIG. 13 DC CURRENT of FUEL CELL

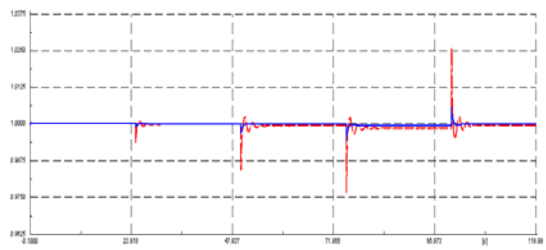

FIG. 14 VOLTAGE CURVE OF AC TERMINAL CONNECTED TO THE LOAD

WITHOUT HUBRID SYSTEM;____WITH HYBRID SYSTEM

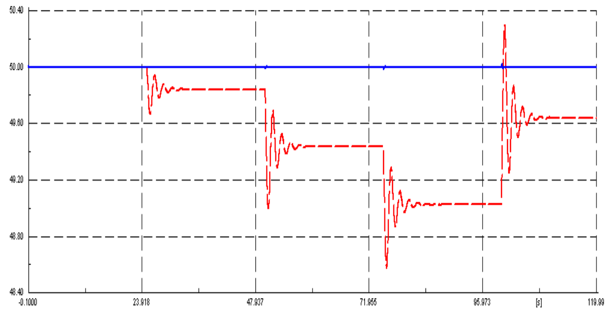

FIG. 15 FREQUENCY CURVE OF AC TERMINAL CONNECTED TO THE LOAD

- - - - WITHOUT HUBRID SYSTE______WITH HYBRID SYSTEM

Using this method, variations of fuel cell terminal dc voltage and the dc current extracted from the fuel cell remain close to the nominal voltage and current (Figs 12 and 13). In order to check the effect of the proposed hybrid system on the network, this hybrid system was connected to an island network consisting of a load, a gas turbine and abrupt variations of load, in which the active and reactive power in different times were applied. Figures 14 and 15 show the curves of voltage and frequency ac terminal to which load is connected. Simulation results for duration of 200 seconds are presented in Figures 9 to 15.

Conclusions

Simulation results implied that in the proposed control method, the respective hybrid power generation system is capable to immediately supply the demanded power and provide a highly favorable dynamic response in the case of sudden load variation. Furthermore, generation power of fuel cell did not increase suddenly which created favorable performance conditions for the fuel cell so that it had sufficient time to supply the needed power and as well DC voltage of its terminal remained around the nominal value. Consequently, an appropriate performance was achieved for fuel cell inverter.

Also by placing this proposed hybrid system in the network, an improvement in the controlling voltage and frequency of island network was achieved in comparision with the state. The absence of that system showed high performance of hybrid system, eliminated steady state fault of governer of gas turbine and minimum deviation of nominal frequency. On the other hand, hybrid system had an influence on the performance voltage regulation of gas turbine and the value of voltage also stabilized in the nominal value.

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List of Symbols Used in the Paper

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

$K_r a$ 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

$q_{H_2}^{in}$ Input fuel flow

$q_{H_2}^{r}$ output fuel flow

$q_{H_2}^{o}$ Fuel flow that reacts

R Ohmic loss

$R_{H\text{-}O}$ 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

Behrooz Ghahremani was born in Bushehr, Iran, on April 20, 1986. He received his BSc degree in electrical engineering from Islamic Azad university, bushehr Branch, Bushehr, Iran, in 2010. Since 2010 he is a MSc student in electrical engineering at Najaf Abad Branch, Islamic Azad University Isfahan, Iran.

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Saed Abazari was born in Shahrekord, Iran on October 25, 1967. He received his BSc degree in electrical engineering from Isfahan University Of Technology (IUT), Isfahan, Iran, 1989 and his MSc in electrical engineering from Ferdowsi University, Mashhad, Iran, 1992 and his PhD in electrical engineering from sharif university, Tehran ,iran, 2002.

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