Active Control of a Hybrid Fuel Cell-Battery System

A. Nasiri, V. S. Rimmalapudi, and A. Emadi

Grainger Power Electronics and Motor Drives Laboratory
Electric Power and Power Electronics Center
Illinois Institute of Technology
Chicago, IL 60616-3793, USA
Phone: +1/(312)567-8940; Fax: +1/(312)567-8976
E-mail: emadi@iit.edu

D. J. Chmielewski and S. Al-Hallaj

Chemical and Environmental Engineering Department
Illinois Institute of Technology
Chicago, IL 60616-3793, USA
Phone: +1/(312)567-3537
Fax: +1/(312)567-8874
E-mail: chmielewski@iit.edu

***Abstract*—A hybrid system of a fuel cell and battery connected to a non-linear load is presented in this paper. As the load is subject to change drastically, a control system is designed to protect the fuel cell against sudden change of load power. In order to design control system, numerous experiments have been performed on fuel cell and battery to determine the time constants. Modeling and analysis of the system as well as simulation and experimental results are presented.**

Keywords- battery; DC/DC converter; digital control; fuel cell.

I. INTRODUCTION

Fuel cells have emerged as one of the most promising technologies for meeting new energy demands. They are environmentally clean, quiet in operation, and highly efficient for generating electricity. This shining new technology provides the impetus towards a huge market for power electronics and its related applications [1]-[3]. Using fuel cell technology needs establishing suitable interface with the system. Sensitive electronic loads, which have non-linear characteristics, need precise regulated voltage. Usually, these loads have sudden changes in power demand. On the other hand, fuel cells do not work properly under transient conditions. The sharp changes in power demand of the load cause sever electrochemical and thermal non-uniformities in fuel cells. These non-uniformities increase the degradation rate of the construction material and eventually reduce the expected life span of the cells. To mitigate these detrimental effects, a battery bank is used along with fuel cells. A DC/DC bi-directional converter is used to connect the battery to the system. When sudden changes occur in the load power, the fuel cell still works at its nominal power and the battery provides the differences. If the power of load increases, the battery supplies the load through the bi-directional DC/DC converter. On the other hand, when the load decreases, additional power charges the battery. Additionally, when the fuel cell starts working, it needs time to reach its nominal power. At that time, the battery supplies the load. An appropriate control system is designed to adjust the operation of the system.

In this paper, modeling and analysis of a hybrid system of a fuel cell and battery connected to an electronic load is presented. A DC/DC converter is used to regulate the output voltage of the fuel cell. Another DC/DC converter supplies the load from the DC line voltage. In case of AC load, this converter can be a DC/AC inverter. A bi-directional DC/DC converter is used to control the charging and discharging of the battery and adjust the power for the load. The block diagram of the system is shown in Figure 1.

II. FUEL CELL SYSTEM

A fuel cell is typically similar in operation to a conventional battery, although they have some distinct physical differences. Primarily, a fuel cell is an electro-chemical device wherein the chemical energy of a fuel is converted directly into electric power. The main difference between a conventional battery and a fuel cell is that, unlike a battery, a fuel cell is supplied with reactants externally. As a result, whereas a battery is discharged, a fuel cell never faces such a problem as long as the supply of fuel is provided. The most popular type of fuel cell is the Hydrogen-Oxygen fuel cell.

Fuel cells have many favorable characteristics for energy conversion. They are environmentally acceptable due to a reduced value of Carbon Dioxide (CO_2) emission for a given power output. Typical values of efficiency range between 40%-85%. Another advantage of fuel cells is their modularity. They are inherently modular, which means that they can be configured to operate with a wide range of outputs, from 0.025 – 50 MW for natural gas fuel cells to 100 MW or more for coal gas fuel cells. Another unique advantage of fuel cells is that hydrogen, which is the basic fuel used, is easily acquirable from natural gas, coal gas, methanol, and other similar fuels containing hydrocarbons. Lastly, the waste heat/exhaust can be utilized for co-generation and for heating and cooling purposes [4], [5].

The PEM fuel cell is used in this project, which is from H Power Corporation. The electrolyte of a PEM fuel cell consists of a layer of solid polymer, which allows protons to be transmitted from one side to the other. It basically requires hydrogen and oxygen as its inputs. Therefore, the oxidant may also be ambient air. These gases must be humidified. A very simple depiction of this type of fuel cell is shown in Figure 2. The anode conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit.

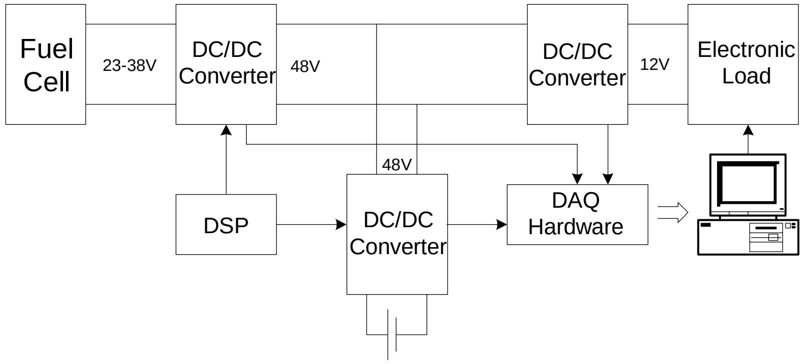

Figure 1. The fuel cell-battery system.

The cathode, on the other hand, has channels etched into it, which distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water. The electrolyte is the proton exchange membrane. This specially treated material only conducts charged ions. The membrane blocks electrons. In fact, the catalyst is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder coated very thinly onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst is placed facing the membrane. The specifications of the Fuel cell used in this project are shown in Table I.

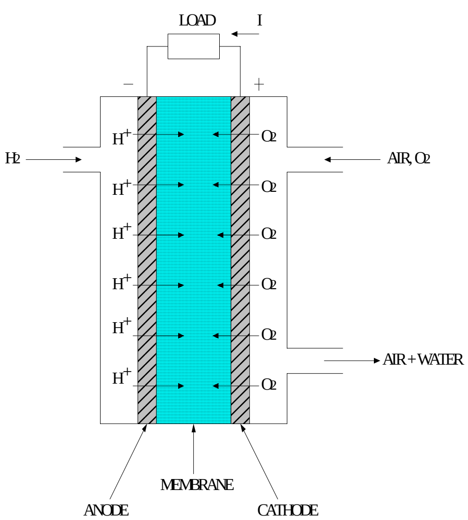

Figure 2. Schematic diagram of a typical PEM fuel cell.

The anode, Cathode, and overall reactions, are as the following.

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall Reaction: $2H_2 + O_2 \rightarrow 2H_2O$

The current output of the fuel cell is determined by the oxidant flow, which is controlled by a DC air pump. Hydrogen pressure at the anode remains at 8psig (0.55bar) for safe operation by a single stage pressure regulator. The amount of current produced is proportional to the volume of air delivered, and is controlled by a microprocessor. A mass flow meter is used to monitor hydrogen consumption. Stack surface temperatures and Hydrogen temperature are monitored with thermocouples. Pressure is monitored with a pressure transducer.

III. Fuel Cell and Battery Testing

A lot of tests were conducted on fuel cell to study the operating conditions and to determine the time constants. An electronic load was connected to the fuel cell stack to perform step changes in current while the fuel cell was operating at steady state. All parameters of the fuel cell stack were held constant except for the load current. Behavior of the system was studied with a step change in the load power. The input pressure, mass flow, and temperature of hydrogen, stack surface temperatures, and fuel cell output current and voltage were measured at 1000 samples/second using Labview program. The circuit diagram of test circuit is shown in the Figure 3.

From the results of the performed tests, a first order dynamical model has been derived for the fuel-cell system. The transfer function of the output power of the fuel cell to the demanded power of the load is as the following.

$$\frac{P_f}{P_L} = \frac{1}{\tau s + 1} \tag{1}$$

Where $\tau = 100mS$. This transfer function is used for designing of the system controllers.

TABLE I. SPECIFICATIONS OF PEM FUEL CELL USED IN THE STUDY.

Manufacture	H Power
Type	PEM
Membrane	Polymer electrolyte
Reactants	Hydrogen and air
Open Circuit Voltage	36V to 38V Nom.
Operating Voltage	27.5V at 11 Amp
Operating Current	11A Nom. 14A max.
Rated Power output at 11 A	302.5W
Peak Power	375 Watts at 14A

The battery system was also tested to achieve the time constant. Primarily, a single Ni-Cd battery was tested to determine its time constant. Then, the time constant of 38-cell series battery bank was investigated using a programmable electronic load. Step changes in current were performed in increments and decrements of 2 from 1 to 7 to determine the time constant. Both the voltage and current signals are given to the DAQ and Labview, which is capable of reading 1000 samples/second. The transfer function of the output power of the battery to the demanded power of the load is as the following.

$$\frac{P_f}{P_L} = \frac{1}{\tau s + 1} \tag{2}$$

Where $\tau = 90mS$.

IV. DC/DC BIDIRECTIONAL CONVERTER

A bi-directional DC/DC converter is used as the interface between the battery and DC line. The topology of the converter is shown in Figure 5. When power from the battery is needed for supplying the load, switch S_1 and diode D_2 are used. Switch S_1 is controlled to adjust the output power of the battery. In recharging mode, when output power of the fuel cell is higher than the power of the load, switch S_1 is turned off and switch S_2 is controlled. This switch reverses the direction of power and recharges the battery. Control schemes for both charging and discharging modes are composed of inner and outer loops. The outer control loop regulates the output voltage of the converter and the inner control loop adjusts the output power. The DSP kit used for the controlling of this converter is TMS320LF2407 from Texas Instruments, Inc. The signals generated from this DSP are eventually used to drive the gates of the switches. The TMS320LF2407 has integrated peripherals specifically chosen for embedded control applications [6]. These include Analog-to-Digital (A/D) converters, PWM outputs, timers, protection circuitry, serial communications, and other functions. Most instructions for this DSP, including multiplication and accumulation (MAC) as one instruction, are single cycle. Therefore, multiple control algorithms can be executed at high speed, thus, making it possible to achieve the required high sampling rate for good dynamic response. This scenario also makes it possible to implement multiple control loops of the inverter in a single chip and increase integration and lower system cost. Digital control also introduces the advantages of programmability as well as immunity to noise and eliminates redundant voltage requirements and current sensors for each controller.

A typical PI controller is shown in Figure 4 and made in the DSP as the following.

$$U(t) = K_P e(t) + K_I \int_0^t e(t) \tag{3}$$

Using Laplace transform, equation (1) is converted to the frequency domain.

$$U(s) = (K_P + \frac{K_I}{s})E(s) \tag{4}$$

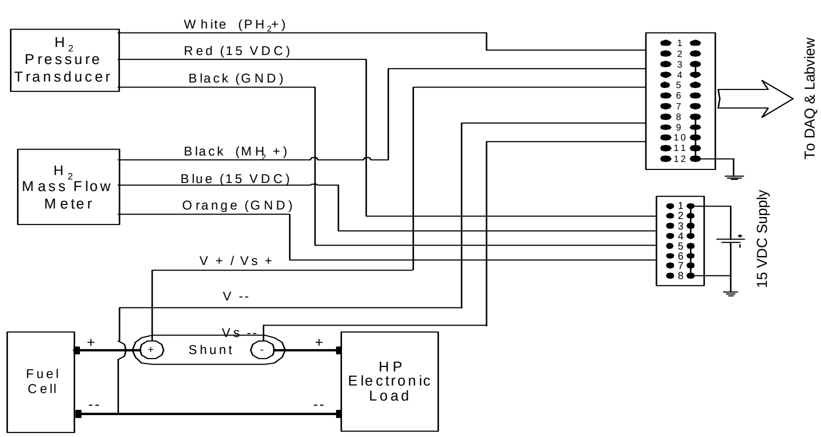

Figure 3. Diagram of the fuel cell testing circuit.

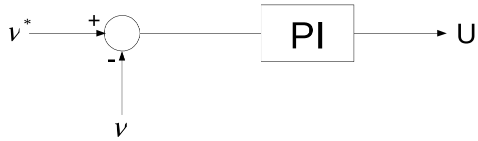

Figure 4. A typical PI controller block diagram.

The differential equation is transferred to difference equation by substituting $s=\frac{1-z^{-1}}{T}$. T is the sampling period of the DSP.

$$U(z)(1-z^{-1})=[K_P(1-z^{-1})+K_I T]E(z) \quad (5)$$

Equation (5) can be written in discrete time as the following.

$$U(k)=U(k-1)+[K_P+K_I T]E(k)-K_P E(k-1) \quad (6)$$

V. System Analysis

A controller is designed to adjust the output power of the fuel cell and battery. The control parameters of the system are designed to remove any sudden change in the output of the fuel cell system. In the system, two different functions can be considered for the fuel cell. In the first one, a constant output power is considered for the fuel cell. Output power of the battery is achieved from the following equation.

$$P_b^* = P_L - P_f^* \quad (7)$$

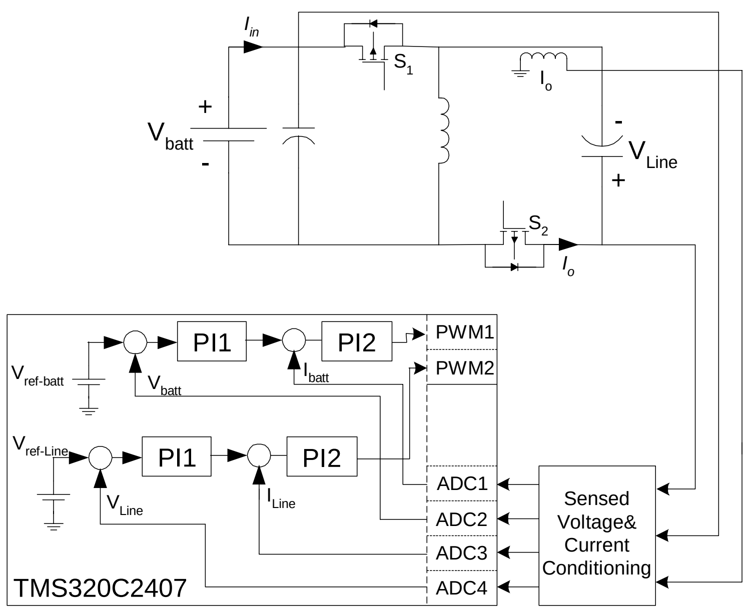

Figure 5. The bi-directional DC/DC converter.

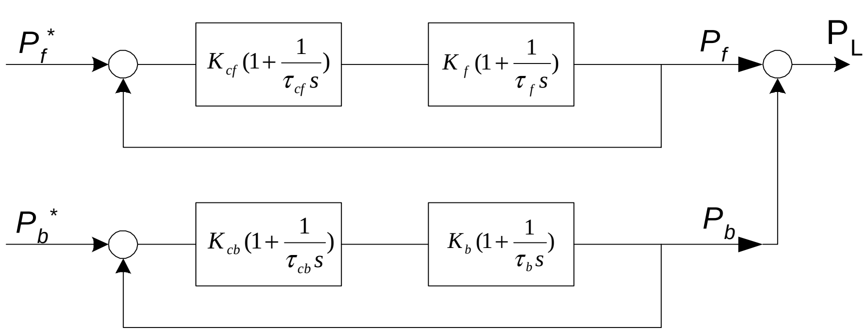

Figure 6. Block diagram of the system controller.

If the load power is more than the output power of the fuel cell, the battery supplies the rest of the power through the bi-directional DC/DC converter. If the load power is less than the output power of the fuel cell, the extra power recharges the battery. In this functionality, fuel cell does not contribute in load change and battery adjusts the power for the load. In second functionality, fuel cell follows the load by a slow controller. Output power of the fuel cell is considered the power demand of the load. The battery is only used to deal with the sudden changes in the load power. If the power of the load exceeds the output power of the fuel cell, the battery provides the extra power. The block diagram of the control system is shown in Figure 6. The parameters for the controller are designed for the optimum operation of the system as the following.

$$K_{cb} = 1 \qquad (8)$$

$$\tau_{cb} = 0.09 \qquad (9)$$

$$K_{cf} = 0.001 \qquad (10)$$

$$\tau_{cf} = 1000 \qquad (11)$$

VI. Simulation and Experimental Results

A 450W, 48V system has been simulated and implemented and the results are shown in Figures 7 and 8. The step response of the system is shown in the Figure 7. When the sudden change occurs in the load power, the battery supplies the load through the DC/DC converter and allows the output power of the fuel cell increase gradually.

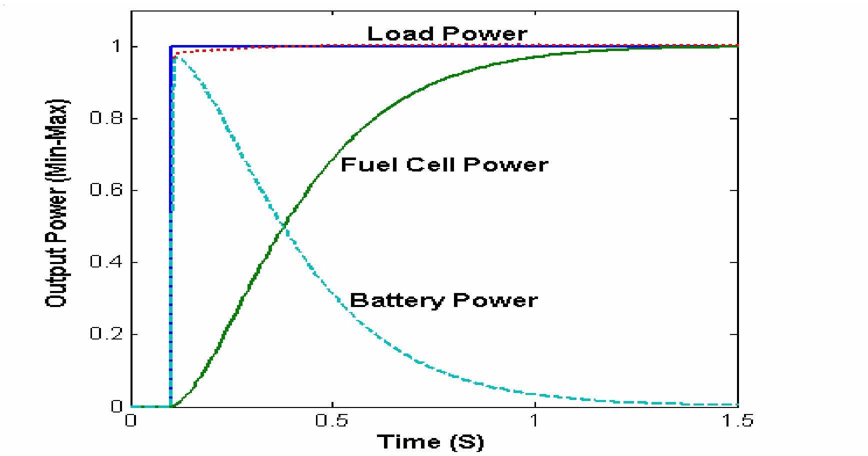

Figure 7. The step response of the proposed control system.

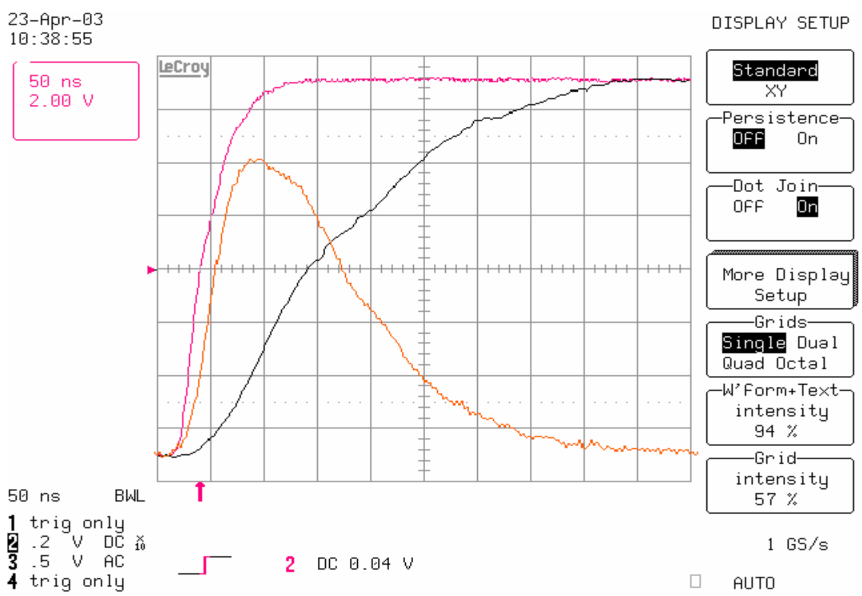

Figure 8. Experimental result, current of load, current of fuel cell, and current of battery.

VII. Conclusion

In this paper, a hybrid system of fuel cell and battery has been discussed. Fuel cell and battery systems have been described and their time constants have been determined by numerous tests. A digital controller has been designed using DSP to protect the fuel cell against the sudden changes of load. Modeling and analysis of the system have been explained and simulation and experimental results are presented.

References

[1] R. Anahara, S. Yokokawa, and M. Sakurai, "Present status and future prospects of fuel cell power systems," *Proceedings of IEEE*, vol. 81, no. 3, pp. 399-408, March 1993.

[2] A. T. Raissi, A. Banerjee, and K. G. Sheinkopf, "Current technology of fuel cell systems," in *Proc. 32nd Intersociety Energy Conversion Engineering Conf.*, vol. 3, Honolulu, Hawaii, Aug. 1997, pp. 1953-1957.

[3] R. H. Goldstein, "EPRI 1990 Fuel Cell Status," in *Proc. 25th Intersociety Energy Conversion Engineering Conf.*, vol. 3, Reno, Nevada, Aug. 1990, pp. 170-175.

[4] T. Rehg, R. Loda, and N. Minh, "Development of a 50kW, high efficiency, high power density, co-tolerant PEM fuel cell stack system," in *Proc. 15th Annual Battery Conf. on Applications and Advances*, Long Beach, California, Jan. 2000, pp. 47-49.

[5] P. G. Grimes, "Historical pathways for fuel cells," *IEEE Aerospace and Electronic Systems Magazine*, vol. 15, no. 12, pp. 7-10, Dec. 2000.

[6] H. Janakiraman, "Programming examples for the 24x/240xA CAN," *Application Report of Advanced Embedded Control Group of Texas Instrument*, SPRA 890, Jan. 2003.