Fuel Cell/Battery/Supercapacitor Power System Control

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Abstract—**Fuel cell along with energy storage devices is a very promising source of clean energy power system. One main weak point of the fuel cell is its very slow dynamics. To overcome this limitation, energy storage devices are used.The energy storage devices used in this paper are battery and supercapacitor. Battery has a very good charge storage capacity and supercapacitor has high current density making them the ideal choice.DC/DC converters are designed for the power electronics interface. The integrated control of these three power sources is a very challenging task for the control system designer. In this paper we do a comparative study of two efficient control systems, one which usesfuzzy logic control and the other is amultilevel supervisory control. All the simulationsare carried out in the matlab/simulink environment.**

Keywords——**Battery, supercapacitor, hybrid fuel cell, fuzzy logic, supervisory control.**

I. INTRODUCTION

Fuel cells have been widely studied and consideredas a promising alternative power source for the future due to theincreasing energy crisis and environmental concerns. They convert the chemical energy into electrical energy.Fuel cellshave shown promising potential for many areas of applicationssuch as those in portable electronics, hybrid electric vehicles,all-electric ships, remote telecommunication facilities, remotegroundsupport stations for aircrafts of space crafts, etc. There are different types of fuel cells available like SOFC, PEM fuel cells, alkaline fuel cell, molten carbonate fuel cell etc. based on the fuel used. Advantages of fuel cell are its high efficiency, fuel flexibility, long term stability, low emission and ability to employ cogeneration. They also have some limitations due to their slow dynamics to load change and high initial cost. To overcome the slow response of fuel cell we integrate it with energy storage devices like battery and supercapacitor. Solid oxide fuel cells (SOFC) show great potential in stationary power applications.Proton Exchange Membrane Fuel Cells (PEMFC) can be used as primary power sources to drive a Fuel Cell Hybrid Electric Vehicle.

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or any other oxidising agent. Hydrogen is the most common fuel. SOFC is an electrochemical conversion device that produces electricity directly from oxidising fuel with solid oxide or ceramic as the electrolyte. A supercapacitor is an electrochemical capacitor with relatively high energy density their energy density is hundred times more than conventional electrolytic capacitors. Supercapacitors also have high power density than batteries or fuel cells. The rechargeable battery used here is the lithium ion battery which is popular for portable electronics, with one of the best energy densities, no memory effect and a slow loss of charge when not in use.

II. SYSTEM DESCRIPTION

A. Modeling ofSOFC

The inputs to the SOFC model are flow rate and pressure of hydrogen and air. Outputs are voltage and temperature of the fuel cell stacks. The inlet temperature of hydrogen and oxygen act as the input disturbance.

To calculate the reversible potential we use the Nernst equation given by [3]

$$E_{cell} = E_{0,cell} - \frac{RT}{4F} \ln \left(\left(\rho_{H_2O}^{ch} \right)^2 * \left(\rho_{O_2}^{ch} \right) / \left(\rho_{H_2}^{ch} \right)^2 \right) \quad (1)$$

Where, R is the gas constant, F is Faraday's constant, T is temperature in Kelvin, and$\rho_{H_2O}^{ch}$, $\rho_{O_2}^{ch}$, $\rho_{H_2}^{ch}$ are respectively the partial pressures of water, oxygen and hydrogen.

The output voltage of fuel cell stack is given by the reversible potential of the cell subtracted from the activation, ohmic and concentration loss [3].

$$V_{out} = N_{cell}V_{cell} = E_{cell} - V_{act} - V_{conc} - V_{ohmic} \quad (2)$$
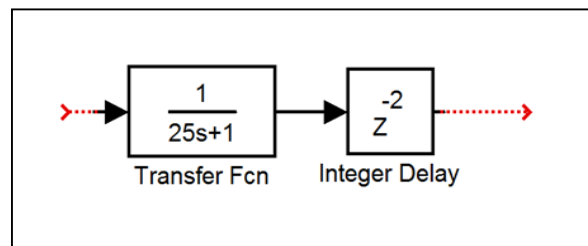
B. Modeling of Fuel Processor

Fig.1 Fuel processor and delivery model

The fuel processor is modelled as a first order system. A two seconds time delay is given to represent the delay associated with the fuel delivery system.

C. Modeling of Battery

The battery model available in the simpowersystem toolbox of matlab/simulink is used here. The battery consists of a controlled voltage source in series with a constant series resistance as shown in Fig.2.
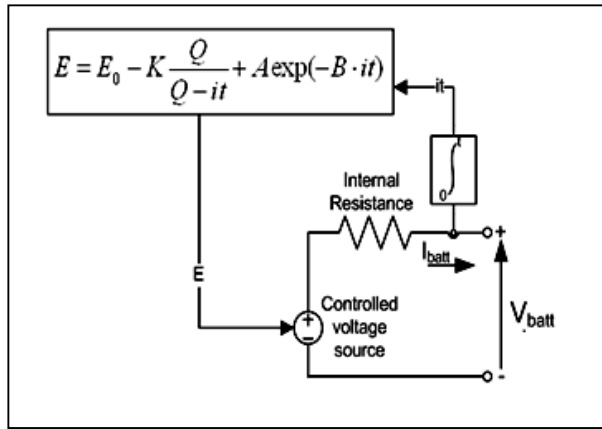

Fig. 2 Battery model

The controlled voltage source is described by the equation [4]:

$$E = E_0 - K \frac{Q}{Q - \int idt} + Aexp(-B. \int idt) \qquad (3)$$

Where E is the no-load voltage, E_0 is the battery constant voltage, K is the polarization voltage, Q is the battery capacity, $\int idt$ is the actual battery discharge, A is the exponential zone amplitude, B is the exponential zone time constant inverse, V_{batt} is the battery voltage, R is the internal resistance and i is the battery current. Fig.3 shows the discharge curve for Lithium-ion battery.
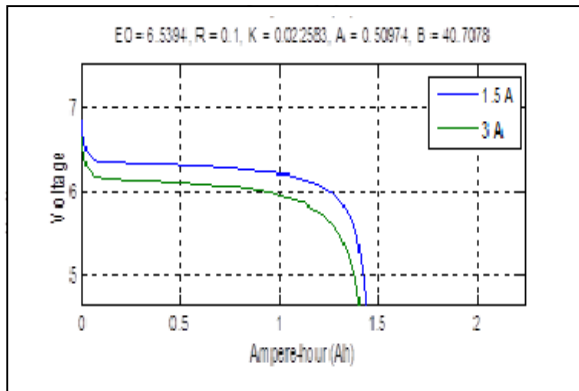

Fig. 3 Discharge curve of lithium-ion battery

The state of charge of the battery is given by [4],

$$SOC = 100 \left(1 - \frac{\int_0^t idt}{Q}\right) \qquad (4)$$

D. Modeling of supercapacitor

The supercapacitor is modelled in Simulink using a capacitance, equivalent series resistance and an equivalent parallel resistance. The equivalent series resistance represents losses during charging and discharging and equivalent parallel resistance represents losses due to self-discharge. Fig.4 represents the Simulink model of the supercapacitor.

The state of charge of the supercapacitor is given by [5],

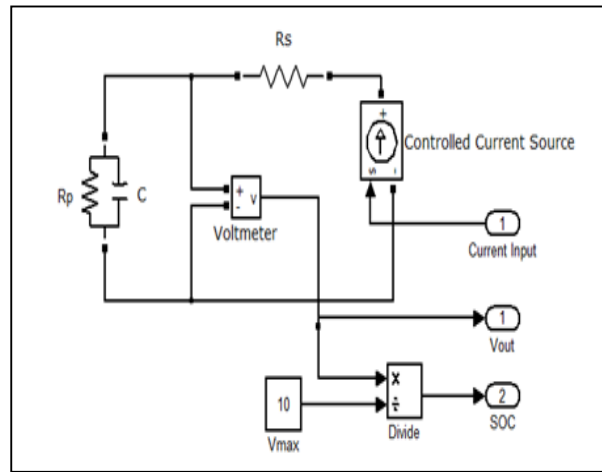$$SOC = \frac{V_{out}}{V_{max}} \times 100 \qquad (5)$$

Fig.4 Supercapacitor model

E. Modeling of DC/DC converter

A schematic model of a unidirectional boost DC/DC converter to be interfaced to the fuel cell is shown in Fig.5. Two bidirectional DC/DC converters to be interfaced to the battery and supercapacitor are also seen.

In the figure all the three converters used are bidirectional itself. Bidirectional feature of the converter interfaced to the fuel cell is disabled by turning the transistor signal off for the upper IGBT. Bidirectional converters have two modes of operation- buck mode and boost mode. Boost mode is the mode of operation when power flows from source to load. Buck mode is the mode of charging the battery and supercapacitor.
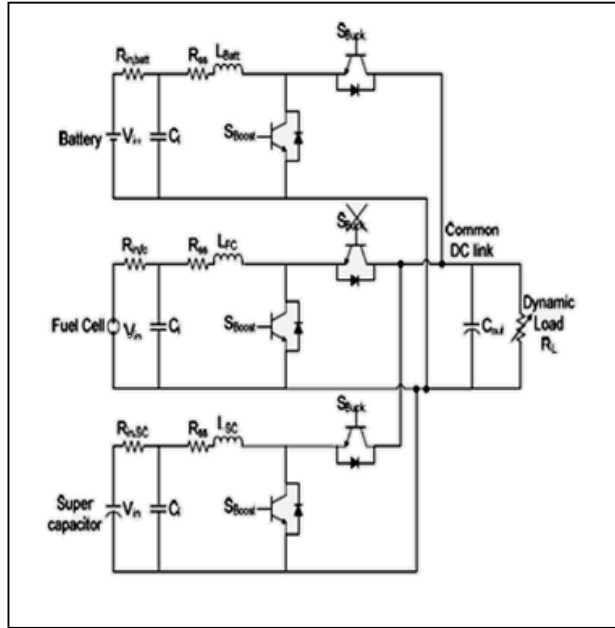
Fig.5 DC/DC converter model

III. SUPERVISORY LEVEL CONTROL STRATEGY

When a system becomes complex, it is very difficult to develop a mathematical model for the system and control. So it is better to divide the system into multiple levels and then control. Fig.6 shows the overall control structure of the hybrid system.

A. Higher Level Supervisory Controller

The higher level controller is divided into two levels. First level identifies the mode of operation based on the status of individual components. The second level is incorporated with intelligent systems that determine how the individual components should perform in that mode of operation. The different modes of operation are standby mode, transient mode, supercapacitor charging mode, normal mode, and battery charging mode.

In the standby mode, all the controllers are disabled except that of the DC/DC converter. When load power increases beyond a certain threshold, controllers switches from standby to transient mode. In this mode of operation, controllers of all controllers are set. Any deficiency in power from fuel cell and battery is automatically supplied by the supercapacitor. Whenever fuel is available control switches to the supercapacitor charging mode. Supercapacitor can be charged to any amount of current as long as its state of charge is not full. Fuel cell supplies power to both the load and supercapacitor at this stage. Whenever there is deficiency battery supplies power. When the supercapacitor is fully charged, controller switches to the normal load. Fuel cell will alone supply power to the load. In this mode battery is disabled, but supercapacitor is still active. If there is any sudden increase in load, then controller switches back to the transient mode. There are two ways to switch to battery charging mode. The switch over takes place either when the state of charge of battery is less than the minimum or when there is a sudden decrease in load power and state of charge of battery is less than maximum. Thus when load power decreases, extra power available is used to charge the battery if it is not full.

B. Lower Level Controllers

When the complex control system is divided into multiple levels, the individual components can be modelled and controlled easily. They are the lower level controllers. They include the balance of plant controller and the DC/DC converter controller.
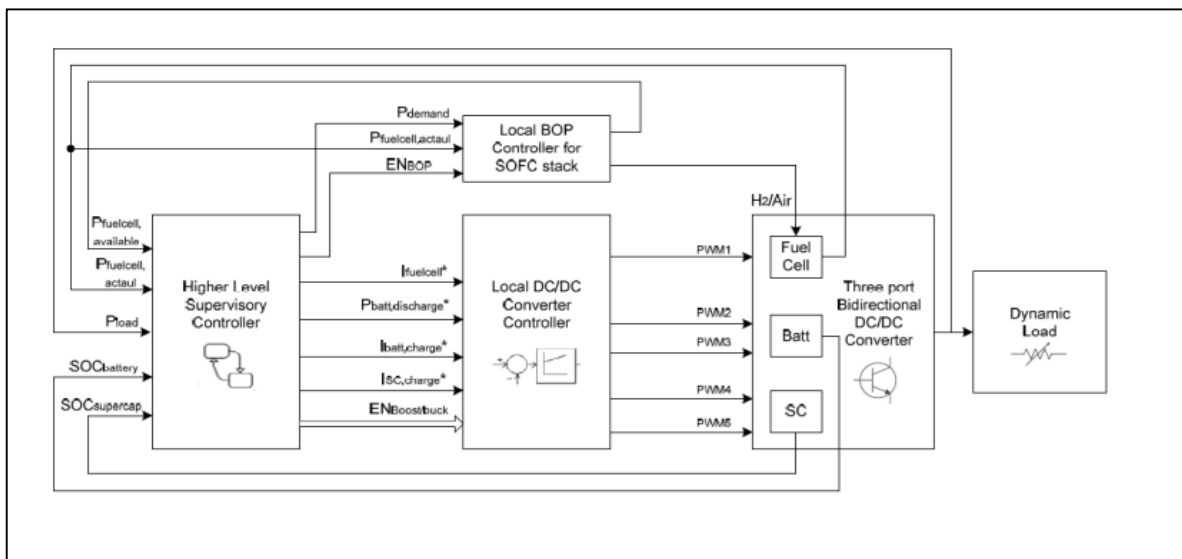

Fig. 6 Overall control system of supervisory controller

Balance of plant controller is enabled in all modes of higher level controller except the standby mode. Only the fuel delivery system and solid oxide fuel cell model is considered here. It receives the reference power to be supplied as the input. Fuel processor is controlled by a PI controller. Output of the fuel processor is fed to the hydrogen input of fuel cell. Air is controlled by open loop feed forward ratio control.

IV. FUZZY LOGIC CONTROL

Fuzzy control provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system.
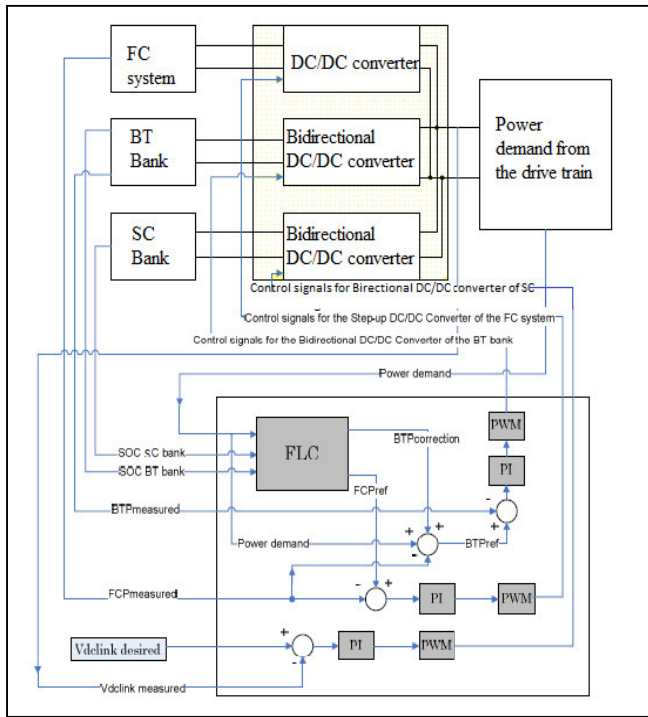

Fig. 7 Fuzzy logic controller block diagram with input and output variable

Fuzzy logic control is a way of relating a set of input variables to outputs that can affect overall system behaviour using "If…then" statements, which are specified according to the designer's knowledge and experience. Fuzzy logic is based on the fuzzy sets theory, which classifies variables with no strict boundaries. A degree of membership is assigned to the variables according to the membership functions definition. The operation of the control strategy can be split into three different functions: satisfy the load demand, ensure the stability of dc link voltage and control the state of charge of the supercapacitor. The fuzzy logic control determines the power coming from the FC system. One of the outputs of the FLC is the fuel cell reference power. If the load is not equal to the power that the power train is providing, the difference is taken from/to the dc-link capacitor. As a result, the dc-link

voltage drops/rises. This effect is counteracted using the energy stored in the supercapacitor. The measured dc-link voltage is compared to its desired value and the error signal is fed to a PI controller that regulates the bidirectional DC/DC converter of the supercapacitor. Battery reference power is calculated. Three PI controllers are used to regulate the duty ratios that govern the Multiple-Input DC/DC converter. Pulse-Width Modulated (PWM) signals control the converters.

V. RESULT

The load demand should be met by the three power sources. Different rules are set for determining the reference power to the fuel cell. It depends on the state of charge of battery and supercapacitor. Fig. 8 shows the rule viewer obtained from the fuzzy logic controland fig.9 shows the battery reference power for the system.
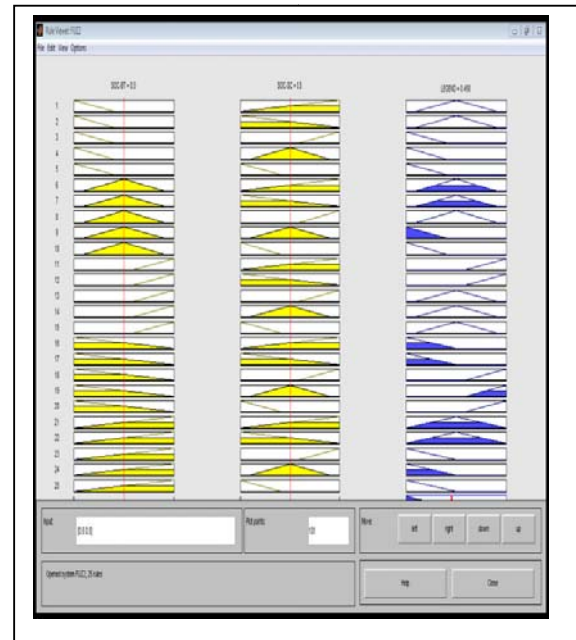

Fig. 8Rule viewer of fuel cell reference power in fuzzy logic control

When the load is very low, the battery is charged depending on its state of charge. When the load powerincreases, initial charge is provided by the supercapacitor until the fuel cell is ready to take over. The supercapacitor recharges whenever there is extra power available and its state of charge is less than the minimum.
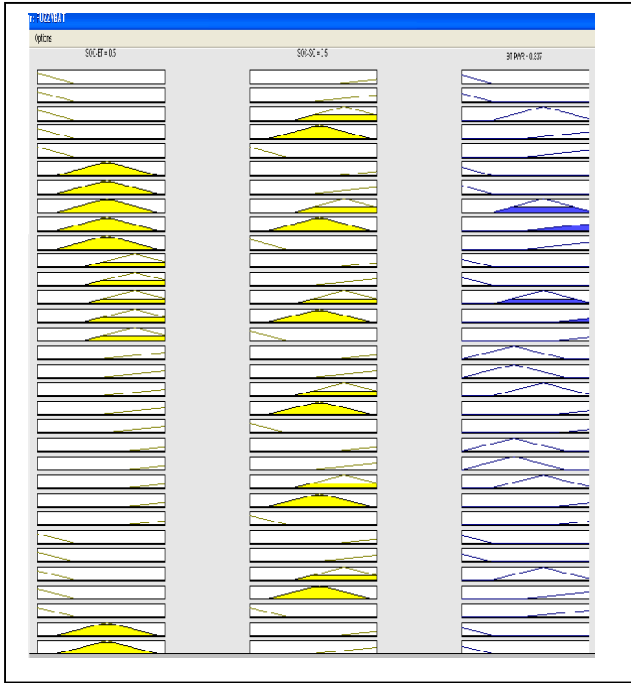
Fig. 9Rule viewer of battery reference power in fuzzy logic control

VI. CONCLUSION

In this paper a study of two control methods for fuel cell/battery/supercapacitor power system is conducted. The supervisory control mechanism using SOFC is suitable for stationary power applications due to its high efficiency. Such a control reduces the complexity of the system by breaking it into multiple hierarchies. Fuzzy logic control using PEMFC is used as power sources for hybrid electric vehicles mainly due to their zero emissions and quiet operation. Fuzzy logic basis is easy to understand, is expressed in natural languageand is very useful to control nonlinear systems. Supervisory control of hybrid fuel cell power system is currently under study.

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