Improvement of Fuel Cells Dynamic Response in Micro-Grids Using Ultra Capacitors

Pouria Maghouli*[1], Hossein Refahi[2]

Abstract – Fuel Cells do not respond to higher frequency contents of load changes due to their inherent large time constants; thus, if any disturbance occurs in the system loading, it would cause negative effects on power quality of the system. This is especially of high importance in microgrids which contain critical loads with low inertia requirements. Sudden changes in load points could cause significant frequency and voltage variations. Hence, proper measures such as energy storage systems should be taken into microgrids for improving their stability. In this paper, a new method based on Ultra-Capacitor (UC) with bidirectional converter has been proposed to solve this drawback of fuel cells. The UC is used to modify the system's frequency response with a fast and efficient controller. The proposed method is simulated for a sample test system in MATLAB/SIMULINK environment and results are presented to illustrate its performance. Based on the results, the system can manage its frequency and voltage variations effectively by the proposed configuration.

Keywords: Fuel Cell, Ultra-Capacitor (UC), PEMFC (Proton Exchange Membrane Fuel Cell), Double layer effect, Utilization Factor (UF).

I. Introduction

One of the most important shortcomings of Fuel Cells is their slow-response to rapid load changes. As a result, they need energy storage systems, which can supply or absorb high density of energy. This can be realized by an Ultra-Capacitor (UC).Fuel cells can be equipped with electrical energy Storage Systems(ESS) to increase their ability to meet dynamic needs of electric loads; this, I turn, will help fuel cells to satisfy the utility constraints and make them more marketable. Today, there are two main types of ESSs available in the market: batteries and UC. Batteries have been used for decades in distributed (mostly renewable) power systems. They have high-energy storage densities, but low-power densities compared to UCs. Batteries often require significant maintenance and have short lifetimes under highly cyclic applications [1]. I comparison to UCs, the most important weakness of batteries which make them inappropriate for usage in FC systems is that they are not able to be charged and discharged rapidly [2]-[3].

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Received 2017.11.19 ; Accepted 2018.12.29

Fuel cells have been modeled in different references [4]-[5]; however, they are direct dynamic. In this paper, a dynamic model will be proposed for fuel cells, and the overall system behavior will be investigated in the presence of UC. To this end, first, the slow dynamical response of fuel cell against rapid changes of loads is illustrated through simulation. Then, effectiveness of UC and bidirectional converter on the overall system behavior will be shown as, in this case, fuel cells are able to provide appropriate high frequency response; this feature can considerably improve the microgrid stability. The results are demonstrated via computer simulations in MATLAB/SIMULINK.

Configuration of ESS

Fuel cell is a DC source with low output voltage compared to the distribution voltage, so a boost DC-DC converter is required as an interface between the three phase inverters of the microgrids. Because of the large time constant of fuel cells in releasing energy into the grid, a bidirectional converter should be inserted before the boost converter at the output terminals of the system. This configuration is suitable to improve the fuel cell dynamic characteristics. Fig.1 illustrates the configuration of the bidirectional system connection between the fuel cell and microgrid.

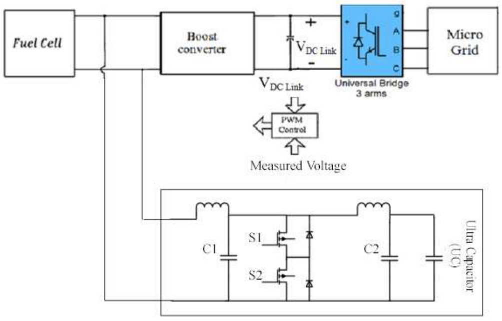

Fig.1: Configuration of the proposed method.

As simulation will illustrate, the proposed configuration is capable to transfer energy to the load rapidly. In the proposed method, the switching of bidirectional converter is based on sensing the DC link voltage and comparing it with a given reference. A proportional Integral (PI) controller is used in order damp the final steady-state error of the residual signal. As shown in fig. 2, logic circuits have been used in the model to prevent voltage instability of microgrid, and to increase the useful life time of the UC. One of the logic circuits senses the UC and DC link voltages, and compares them with their nominal values. For example, when the DC link and the UC voltages are either more than 95% or under 80% of their nominal values, the logic circuit sends a command to the bidirectional converter to recharge the capacitor. Another important subsystem, which protects the UC against the full discharge, is a logic circuit that sends a trip command to the UC's protection device. This circuit operates when the UC voltage is less than 10% of its nominal value [6].

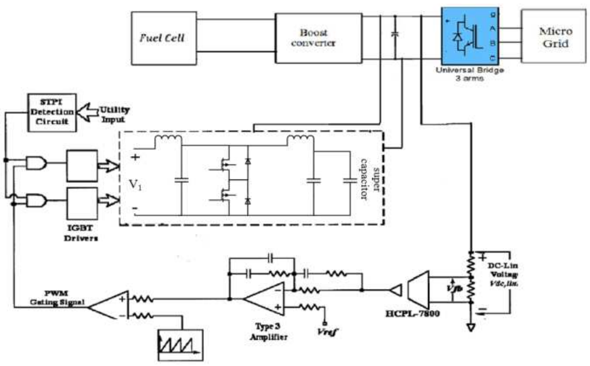

Fig.2: The configuration of the control system.

II. Dynamic Modeling of PEMFC

Fuel cell is an electrochemical device which generates electricity due to chemical reaction of hydrogen and oxygen. Unlike the batteries, fuel cells not only are energy storage systems, but also energy convertors. The density of Fuel cells energy is larger in comparison with batteries and filling the fuel cell hydrogen tank is much easier than charging batteries process. One of the most prevalent fuel cells is polymer electrolyte fuel cell. In the following, dynamic model of polymer fuel cell will be stated. Equation (1), known by Nerst equation, shows the output voltage of fuel cell:

$$V_{FC} = E_{nerst} - V_{act} - V_{conc} - V_{ohmic} \quad (1)$$

by deducing ohmic, activation and concentration voltage drops, through the Nerst voltage, the output voltage will be achieved. The ohmic voltage drop is caused by decreasing of hydrogen concentration.

Enerst can be calculated through equation (2):

$$\mathrm{E_{nerst}} = \frac{\Delta G}{2F} + \{\frac{\Delta S}{2F}(T - T_{ref}) + \frac{RT}{2F} \quad (2)$$

$$\times [\ln(P_{H2}) + \frac{1}{2}\ln(P_{O2}) - \ln(P_{H2o})\}$$

neglecting$\ln(P_{H_2O})$ in (2), we have the equation (3):

$$E_{nerst} = 1.229 - (8.5 \times 10^{-4}) \times (T - 298.15)$$
$$+ 4.308 \times 10^{-5} \times T \times \{\ln(P_{H2} + \frac{1}{2} P_{O2}) - \ln P_{H_2O)}\} \quad (3)$$

where ΔG is Gyps energy (J/mol), ΔS ,the entropy change(J/mol), F, the Farady constant(96485.34C/mol), P_{H_2},$P_{O_2}$and P_{H_2O}, the relative pressure of hydrogen, oxygen and water, respectively, R, is the universal gas constant (8.314 J/mol.k) and T, is temperature of fuel cell (in Kelvin).

III. Ohmic Voltage Drop

The Ohmic voltage drop of a fuel cell can be expressed as the multiplication of the fuel cell current by the resistance caused by the resistivity of electrolyte and other connecting devices:

$$V_{ohmic} = I_{Fc} \times R_{Ohmic} = I_{Fc} \times (R_m + R_C) \quad (4)$$

From Ohm's law, the resistance R_m is:

$$R_m = \frac{r_m \times l}{A} \quad (5)$$

The resistivity of Nafion series proton exchange membrane can be calculated as [6]:

$$\rho_M = \frac{181.6[1+0.03\left(\frac{i_{Fc}}{A}\right)+0.062\left(\frac{i_{Fc}}{A}\right)^{2.5}\left(\frac{T}{303}\right)^{2}]}{[\varphi-0.634-3\left(\frac{i_{Fc}}{A}\right)]\times \exp\left(4.18\left(\frac{T-303}{T}\right)\right)} \quad (6)$$

where, φ is the relative humidity and stoichiometry constants, approximately equal to 14 in 100% humidity condition.

III.2.Activation voltage drop

The activation voltage drop is caused by slow dynamic of chemical reaction on the electrodes' surfaces. V_{act} can be written as:

$$V_{act} = -[\ \xi_1 + \xi_2 T + \xi_3 T \ln(I_{FC}) + \xi_4 \ln(C_{O2})\ ] \quad (7)$$

As shown in (7), the concentration of dissolved oxygen at the gas/liquid interface can be defined by Henry's law. The C_{O_2} can be calculated by:

$$C_{O2} = \frac{P_{O2}}{5.08\times 10^{6} e^{(-\frac{498}{T})}} \quad (8)$$

III.3. Concentration Voltage Drop

Concentration voltage is caused by decreasing in hydrogen and oxygen concentration resulted from hydrogen and oxygen mass transferring. To model this part, the value of J_{max}, the maximum current density related to the maximum fuel cell consumption should be known. This value has been measured about $1000\,mA/cm^2$ [6]. The concentration voltage drop can be calculated by:

$$V_{Conc} = -B \times \ln\left(1-\frac{J}{J_{max}}\right) \quad (9)$$

In (9), B is related to cell parameters and J is the current density of fuel cell. Fig.3 illustrates the voltage drops components of (1). Table I shows the required parameters for fuel cell modeling.

TABLE I: Fuel cell parameters [6].

Parameter	*Value*
A	6.25 [$Cm^2 Cell^{-1}$]
B	0.016 (V)
C	2.5 (F)
F	96486.7 [C(kmol)−1]
Jmax	$1.5\frac{A}{Cm^2}$
NS	176
NP	2
RC	2×10^{-4}
T0,Trt,Tic,Tit	28, 20, 0.7, 4000
U	0.8
ξ1, ξ 2, ξ 3, ξ 4	−0.9514, 0.00312, 7.4×10^{5}, -1.87×10^{4}
Number of series cells	$N_S = 50$
Number of parallel cells	$N_P = 1$

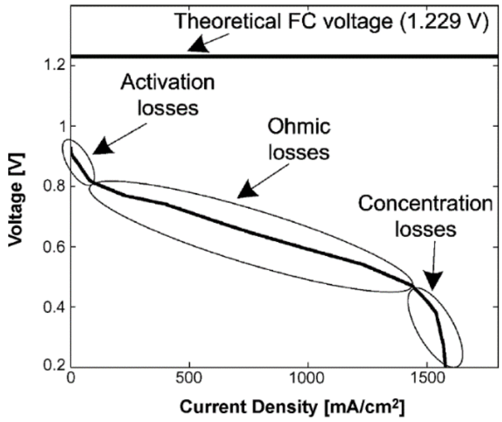

Fig.3: Typical FC polarization curve [6].

IV. Double Layer Effect

Two materials with equal and opposite electrical charges act as a capacitor and electrical charge would transfer between them. This phenomenon occurs in fuel cells, when electrons are transferred from electrode to electrolyte and ions from electrolyte to electrode. This is called double layer effect which creates a large time constant for the fuel cell, so the fuel cell will not be able to track the load current in fast load changes scenarios. To model this effect, a capacitor is added in the fuel cell model [6](fig. 4).

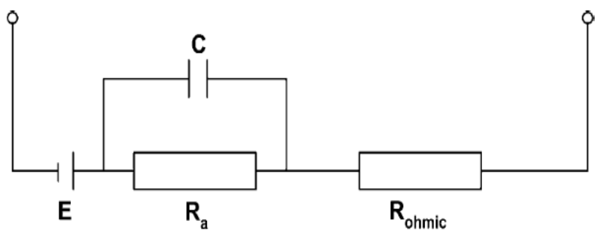

Fig.4: FC electrical equivalent circuit

The capacitance of this capacitor, which is used in simulation too, is assumed 2.5 F [6]. Fig .4 shows the equivalent circuit of the fuel cell [6].

$$V_{Fc} = E_{nerst} - V_{ohmic} - R_a i_{Fc} \quad (10)$$

$$R_a = \frac{V_{act} + V_{Conc}}{I_{Fc}} \quad (11)$$

$$V = R_a i_{Fc} \quad (12)$$

$$R_{ohm} = \frac{V_{ohm}}{i_{Fc}} \quad (13)$$

$$i_{Fc} = C\frac{dV}{dt} + \frac{V}{R_a} \quad (14)$$

$$\tau = CR_a \quad (15)$$

here, τ is the time constant of fuel cell caused by the double layer effect.

Bidirectional Buck-Boost Converter

Fig. 5 shows a bidirectional buck-boost system that is, technically, able to decrease and increase the output voltage level by controlling the Duty cycle. It can be shown that the ratio between the input and output voltages of the converter is:

$$\frac{V_{out}}{V_{in}} = \frac{D}{1-D} \quad (16)$$

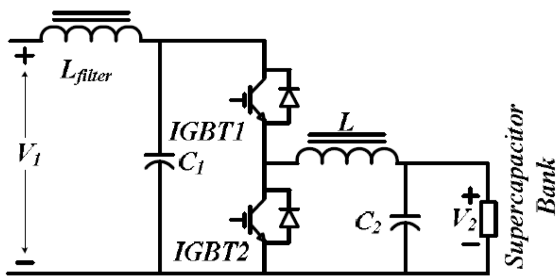

Fig. 5: Bidirectional buck-boost converter used in this work [7].

A. Charging state

In this condition, IGBT1 is turned on and off periodically by the pulse-width modulation(PWM) signal while IGBT2 is kept in off state continuously. Hence, the converter acts as a buck converter which absorbs energy from the power supply and charges the UC. During the charging state, the voltage sensor senses the voltage of the UC and signals the PWM unit, which contains a PI controller to control the voltage of the UC through changing the duty cycle of IGBT1. Figs 6.a-b illustrates this condition.

B. Discharging state.

As illustrated in fig. 6c-d,in discharging state, IGBT1 is kept off continuously, while IGBT2 is turned on and off periodically. In this state, the voltage sensor also transfers the sensed voltage of the UC into the PWM unit in order to keep the DC link voltage approximately constant.

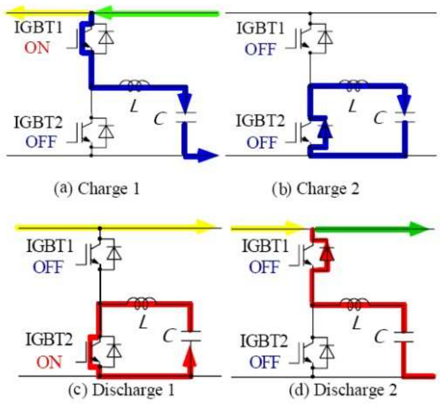

Fig. 6: Operation of the circuit in charge and discharge modes [7].

V. Simulation Results

In this section, the simulation results are presented, showing improvements in the fuel cell performance. Fig 7 shows the output power of the fuel cell while feeding a 1300W load. At t=15 (sec) another 1300 watt load is connected to the microgrid. As it can be seen, the PI controller of the fuel cell tries to increase PH2 and PO2,but due to the slow nature of FC dynamic, it is not able to provide the exact required power instantaneously. The output power and voltage of the fuel cell are shown in figures 7, 8, 9, and 11, respectively. Figures 11, 12, and 13,in turn, show the voltages V_{Ohmic}, V_{act}, and V_{Conc} for the given conditions.

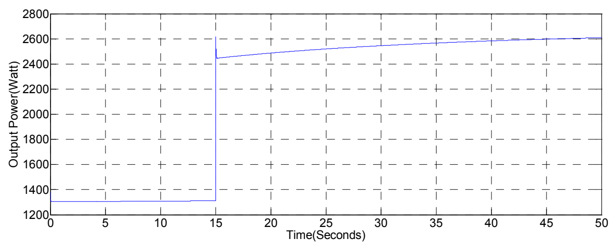

Fig. 7: Output power of the fuel cell.

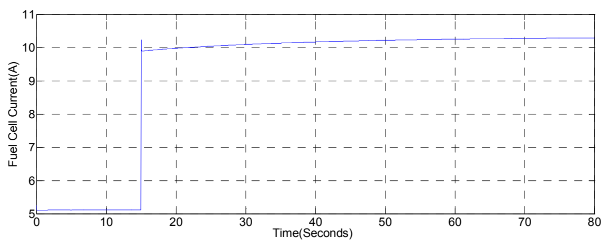

Fig. 8: Output current of the fuel cell.

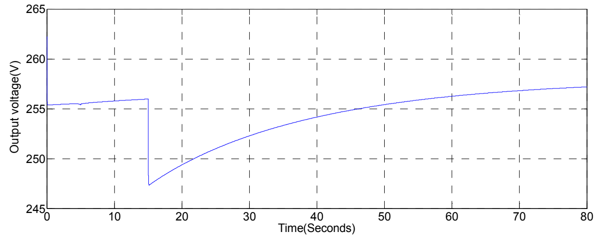

Fig. 9: Output voltage of the fuel cell.

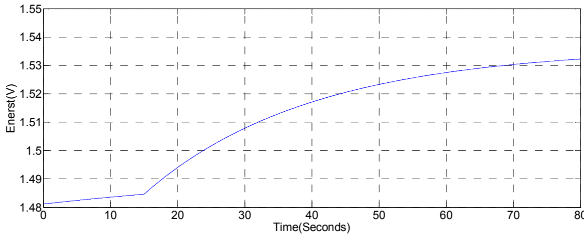

Fig. 10: Enerst of each cell of the fuel cell

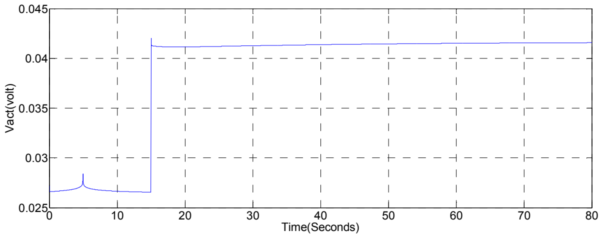

Fig. 11: Vact of each cell

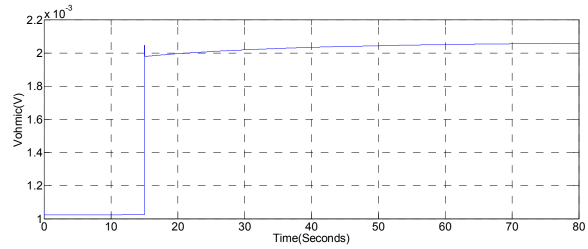

Fig. 12: V ohmic of each cell

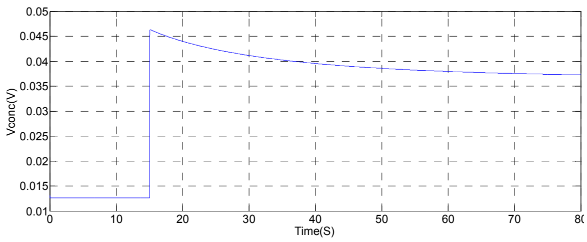

Fig. 13: VConc of each cell.

Form figures 7 to 13, it is obvious that the fuel cell cannot instantaneously produce enough power in response to the sudden load changes. We apply then the proposed configuration to the fuel cell system in a micro grid, as shown in fig 14. The transmission line parameters of the microgrid are given in table II.

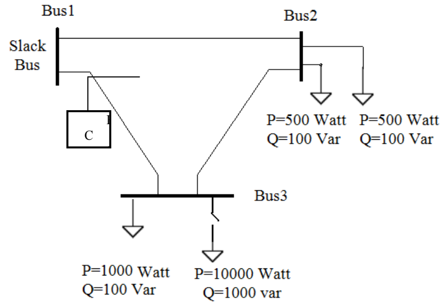

Fig.14: Distribution system used in simulations.

Table II. Line specifications of the assumed system

Parameter	*L (Henry)*	*C (Farad)*	*Length of line*
Value	9.4×10^{-6}	1.27×10^{-9}	1 km

In the figures15-16, it can be seen that the UC, with a suitable control system, is able to compensate for the lack of rapid performance of the fuel cell. At t=35 sec a high-power load (P=10000W & Q=1000 VAR) is connected to bus 3. As Fig. 16 shows, the voltage of slack bus has changed within acceptable range, which is about 12 volts in the worst case. Other bus voltage profiles are the same as the slack bus voltage, which can withhold acceptable performance of the applied power electronic system and the UC. From fig.15, it takes less than a second to compensate for the slow dynamics of the fuel cell. Hence, it is obvious that the control system of the UC has been successful in improving the fuel cell dynamics. Fig.16 illustrates that when a high demand load is connected into bus3 at t=35 sec, the internal voltage of fuel cell (Enerst) increases due to a PI controller (P_{O2} & P_{H2} are increasing), however , it has a very slow response so that it create high inertia for the fuel cell.

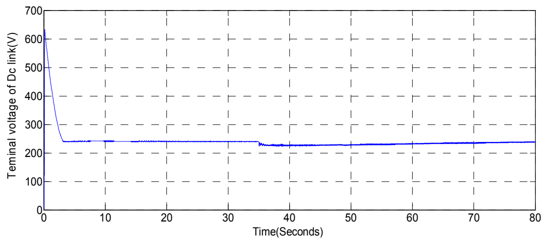

Fig. 15: Terminal voltage of DC link.

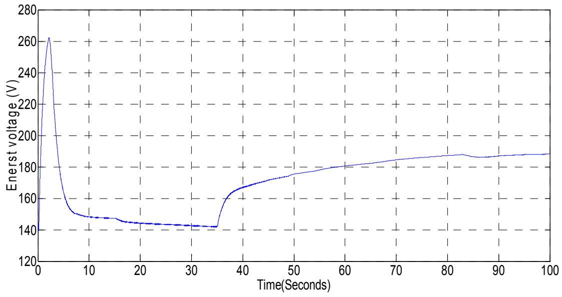

Fig.16: Enerst voltage of the fuel cell.

VI. Conclusion

Fuel cells are not capable to produce energy in rapid load change setups because of technical reasons such as double layer effect. In this article, a new approach based on using Ultra Capacitor (UC) has been proposed in order to solve this drawback of fuel cells. We have modelled the dynamic behavior of the fuel cells, and implemented the model in MATLA/SIMULINK environment. Results from the simulations illustrate slow dynamic of the fuel cell against the rapid load changes. Consequently, incorporating UC and bidirectional converter into the system results in improved response of the fuel cell. This feature equip microgrids with considerable stability.

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