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Maximum Power Point Tracking for Fuel Cell in Fuel Cell/Battery Hybrid Power Systems

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Abstract

Ability of fuel cell systems to produce power is limited. So it is necessary to force the system to operate in conditions which match up with fuel cell maximum power point (MPP). A MPP Tracking (MPPT) controller which utilizes a MPPT algorithm can undertake this duty. When fuel cell operates in this condition, since MPP is a unique and fixed point of operation, load power requirements are not taken into account and output voltage will vary with variations of load resistance. In this paper, a new configuration for Fuel cell / Battery hybrid power system with required controllers is proposed and analyzed. This system works in the way that, fuel cell operates in its MPP and output voltage is kept constant. The proposed system is simulated in two steps, one for verifying performance of MPPT controller and another for voltage regulating controller. Results show acceptable operation of the system under different conditions.

Keywords: Fuel cell, Battery, Maximum Power Point Tracking, Perturbation and Observe, Output Voltage Regulation

1. Introduction

Fuel cells (FCs) are static electric power sources that convert the chemical energy of fuel directly into electrical energy. FCs have advantages such as high efficiency, zero or low emission (of pollutant gases), and flexible modular structure [1, 2]. A large number of internal parameters can impact on produced voltage of FC [2, 3, 4, 5], but in any condition, there is just one unique point on V-I curve which represents MPP. In this point, FC can produce its maximum power. Owing to the limited ability of FC systems to produce power from available fuel flow, it is necessary to force the system to operate in condition which matches to fuel cell MPP. This can avoid excessive fuel consumption and low efficiency operation.

A Maximum power point tracking (MPPT) controller traces the MPP of FC using a MPPT algorithm. The controller generates instructions for a DC-DC converter and a certain amount of current which corresponds to MPP, is extracted from FC.

There are several methods to search extremum value of a function [6, 7, 8, 9, and 10]. Among them Perturbation and Observe (P&O) [6, 7] is the most commonly used method because of its simple algorithm.

In this paper, FC MPPT, its problems and deficiencies, and proposed solution which is a new configuration for Fuel cell/Battery hybrid power system, is presented and analyzed.

In section II, fuel cell power system and its model is reviewed. In section III, the MPPT strategy is analyzed. In next section, section IV, the proposed hybrid system and its control scheme is introduced. The results and conclusion are presented in sections V and VI respectively.

2. Fuel cell power system

FCs are good energy sources to provide reliable power at steady state; however, due to their slow internal electrochemical and thermodynamic characteristics, they cannot respond to electrical load transients as quickly as desired. They are connected to the power grid through power electronic interfacing devices, and it is possible to control their performance by controlling the interfacing devices. Modeling of FCs can therefore be helpful in evaluating their performance and for designing controllers [1].

The internal voltage of an FC is a nonlinear function of the FC current, internal temperature, and pressure of oxygen and hydrogen gasses. Like in batteries, FC output voltage is the difference between its internal voltage and its internal voltage drops, namely the activation, ohmic, and concentration voltage drops. These voltage drops are nonlinear functions of FC current, temperature, and chemical reactions. The basic expression for the proton exchange membrane (PEM) fuel cell voltage is [2, 3]:

$$V_{cell} = E_{nernst} + \eta_{act} + \eta_{ohmic} + \eta_{con} \tag{1}$$

Reversible thermodynamic potential E_{nernst} is described by the Nernst equation. The Nernst equation for the hydrogen / oxygen fuel cell, using literature values for the standard-state entropy change, can be written [4, 5]:

$$E_{nernst} = 1.229 - (8.5 \times 10^{-4})(T - 298.15) + (4.308 \times 10^{-5})T\,(\ln P_{H2} + 0.5\ln P_{O2}) \tag{2}$$

where P_{H2} and P_{O2} are hydrogen and oxygen partial pressure (atm) respectively and T is absolute temperature (K).

Activation overvoltage η_{act} which is dominant at low FC currents is the combination of cathode and anode activation overvoltages. It is due to sluggish electrode kinetics and described by the Tafel equation, which can be expressed as [4]:

$$\eta_{act} = \xi_1 + \xi_2 T + \xi_3 T \ln C_{O2} + \xi_4 T \ln I \tag{3}$$

where $\xi_i (i = 1–4)$ are parametric coefficients for each cell model. C_{O2} is the concentration of dissolved oxygen at the gas/liquid interface (mol cm^{-3}).

Ohmic overvoltage η_{ohmic} is due to the resistance to the flow of hydrogen electrons and positive ions, and (while occurring at all current levels) is more pronounced in the linear portion of the FC voltage current (V-I) characteristic. Ohmic overvoltage can be expressed as [4]:

$$\eta_{ohmic} = -IR_m \tag{4}$$

The ohmic resistance Rm is given by

$$R_m = r_M l / A \tag{5}$$

where r_M is the membrane specific resistivity for the flow of hydrated protons (ohm.cm), A is cell active area (cm^2), and l is the thickness of the polymer membrane (cm), which serves as the cell electrolyte.

Concentration overvoltage η_{con} is due to the inability to move reactants and products fast enough through the electrolyte to and from the electrochemical reaction site. This overvoltage is dominant at high FC currents and can be expressed as [2]:

$$\eta_{con} = -\frac{RT}{zF}\ln\frac{C_S}{C_B} \tag{6}$$

where C_S is the surface concentration and C_B is the bulk concentration. R is Universal gas constant (J $kmol^{-1}$ K) and F is Faraday's constant (C $kmol^{-1}$). According to Fick's First Law and Faraday's Law, the above equation can be rewritten as:

$$\eta_{con} = -\frac{RT}{zF}\ln\left(1-\frac{I}{I_{limit}}\right) \tag{7}$$

where I_{limit} is the limiting current and denotes the maximum rate at which a reactant can be supplied to an electrode.

Hydrogen positive ions and electrons move from anode within electrolyte and external load respectively, and will be collected at cathode surface. So, two charged layers with opposite polarity will be composed within the boundary of porous cathode and electrolyte. These layers, known as two electrochemical layers, can store electrical energy and act as a super capacitor. Considering the capacitance of this capacitor C, the capacitor voltage with respect to activation resistance R_{act} and concentration resistance R_{con} can be calculated by (8).

$$V_C = \left(I - C\frac{dV_C}{dt}\right)(R_{act} + R_{con}) \tag{8}$$

So (1) can be rewritten as:

$$V_{cell} = E_{nernst} - VC + \eta_{ohmic} \tag{9}$$

The output voltage of the fuel cell stack can be calculated by the following expression.

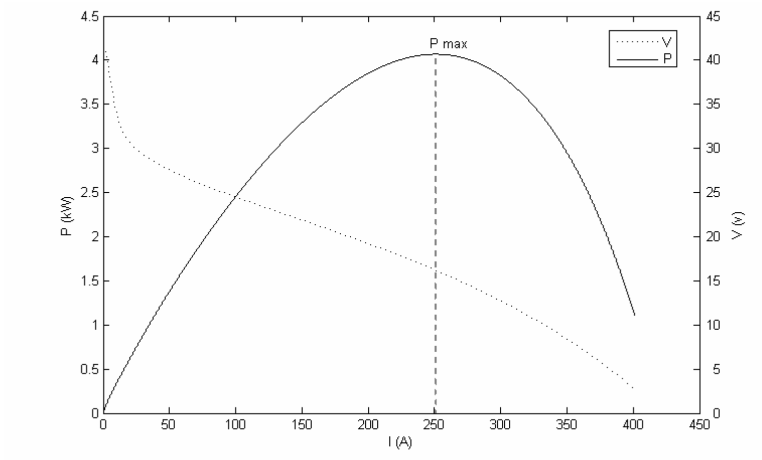
$$V_{stack} = NV_{cell} \tag{10}$$

where N is the number of single cells in stack. The output power of the stack is:

$$P_{stack} = V_{stack}\, I \tag{11}$$

Choosing parameter values from [3], [4] and [5] the stack output voltage and power curves are presented in figure 1.

Figure 1: Fuel cell stack output voltage and power v.s. its current curves



3. Maximum power point tracking strategy

There are various methods to find extremum value of a function (which have been developed mostly for photovoltaic arrays), such as Perturbation and Observe (P&O) [6, 7], Incremental Conductance [8], short-circuit current method [9], and the open-circuit voltage method [10]. Considering its simple algorithm, P&O is the most commonly used method.

In P&O, as can be understood from its name, a perturbation is applied to system and its effect is observed. For FC system, an increment (either positive or negative) in FC current, ΔI, is considered as perturbation and output power variations, ΔP, will be observed. If the output power is increased by a positive constant increment in FC current, further positive increment is needed; otherwise perturbation must be negative. In a similar way, if the output power is increased by a negative perturbation, further negative increment is needed; otherwise direction of perturbation must be changed.

For fast tracking of maximum power point, the perturbation should be selected to be large. This selection leads to more fluctuations in output power. If we want to reduce these fluctuations, the perturbation should be small, but tracking time will be long. So, as a summary, the quick tracking time is in conflict with the suppression of fluctuations in output power. Many approaches have been proposed to improve the P&O algorithm, such as using a variable step size of perturbation instead of a constant value as following [11]:

$$I_{k+1} = I_k + M \frac{\Delta P_k}{\Delta I_k} \tag{12}$$

where M is a coefficient that modifies step size, and I_k, ΔI and ΔP are the current value, deviation of current and deviation of power at Kth sampling period respectively. However, for FC power systems, tracking time should be chosen based on FC dynamic response. In other words, the rate of current changes should not exceed the maximum permissible rate of FC current changes.

It should be noted that, in spite of appropriate behavior of P&O under static conditions, it will not function well if it encounters dynamic behavior of system [6]. To obviate this drawback, continuous changes in FC operation should be avoided.

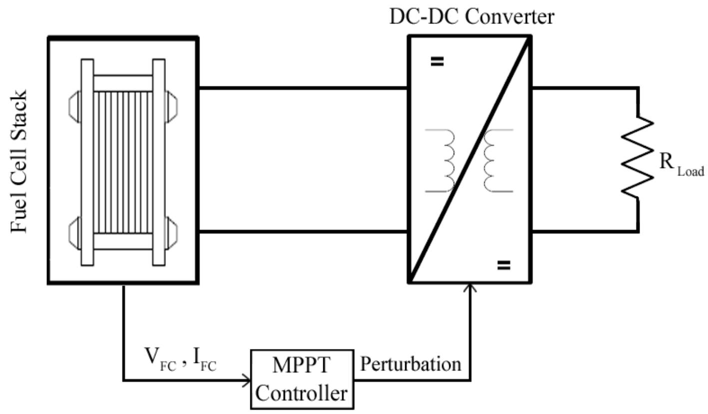
4. Hybrid system and its control scheme

A DC-DC power converter between FC and load can change equivalent load resistance seen by FC. At MPP, current gain of the converter, G, has a value which causes the equivalent load resistance to be equal to the internal resistance of the FC. The relationship between equivalent load resistance R_{eq} and load resistance R_{Load} is:

$R_{eq} = G^2 R_{Load}$ (13)

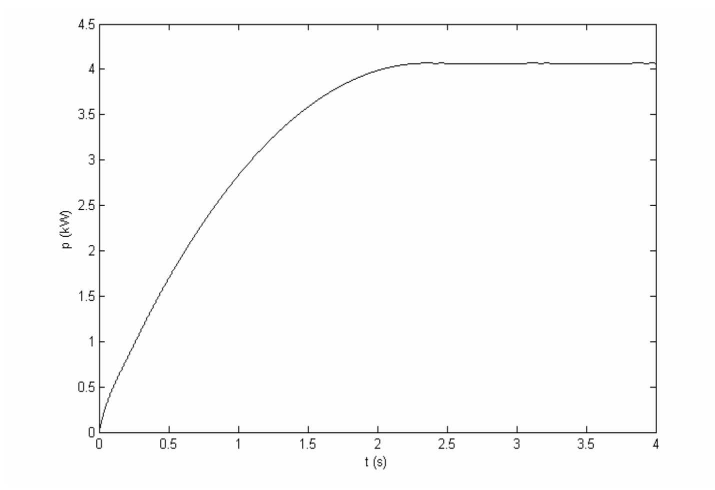
A MPPT controller uses FC voltage, current and subsequently its power, to find MPP and then generates control instructions for the power converter. The converter forces the fuel cell to work at current which defined by MPPT controller and corresponds to MPP of FC. In this point, the equivalent load resistance is equal to the internal resistance of the FC and maximum power can be delivered to load, considering maximum power transfer principle. Figure 2 shows a generic schematic diagram of such a system.

Figure 2: Schematic diagram of MPPT fot FC system



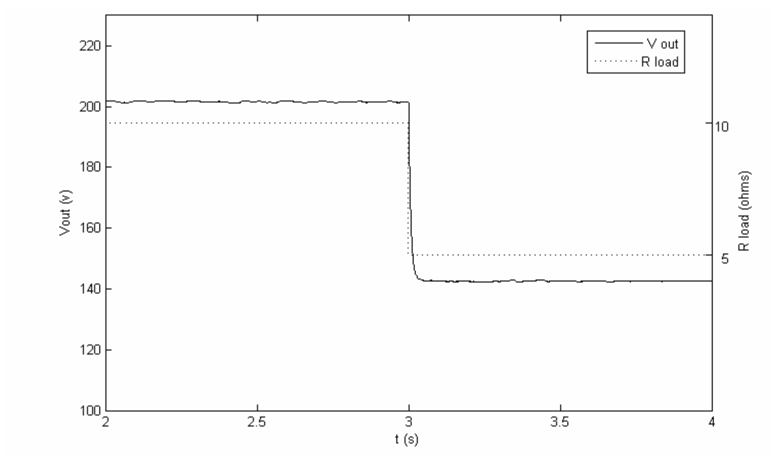
As an example of MPPT for a FC system, Figure 3 shows a plot of the FC stack power for $P_{H2}=P_{O2}$=1 atm and T=70º C. As it can be seen, the MPP is found by MPPT controller and FC is forced to stay in this point of operation.

Figure 3: MPPT for a FC system in standard conditions



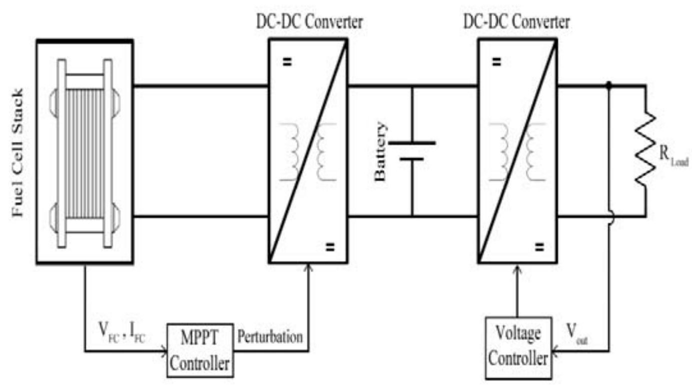
In order to operate in MPP, FC output current should be constant; so, load can receive just a fixed current and power. Consequently, changes in load resistance will result in variations in output voltage. Figure 4 shows the operation of system under variable load resistance condition.

Figure 4: Output voltage variations when load resistance varies



To overcome the described deficiencies, a FC/Battery hybrid system, represented in Figure 5, is proposed.

Figure 5: Compelete proposed FC/Battery hybrid system



In this system, battery is placed in parallel with the first power converter, and keeps the output voltage constant. As mentioned before, MPP is unique and, if output voltage kept constant, load current will vary with variations of load resistance. In such conditions, battery can absorb (or deliver) excessive (or lacking) current and thus, it helps the output voltage to be constant.

However, battery charge (and subsequently the output voltage) can be widely affected if the absorption or generation of current continues for long duration. So, another DC-DC power converter, between battery and load is needed for exact regulating the output voltage. To make instructions for this converter, output voltage is compared with a reference value, and voltage regulation block makes required instructions.

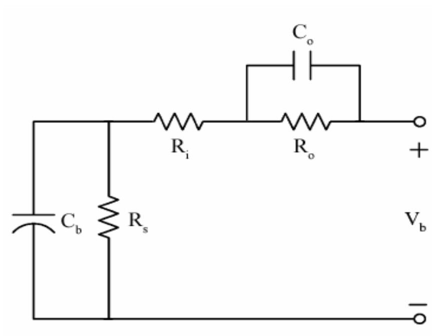
In addition to above mentioned issues, a battery charge controller should be applied. When battery charge reaches its upper or lower limits, this controller interrupts FC or load respectively, to avoid undesirable damages on battery. Anyway, choosing a battery with sufficient capacity, or considering load variations range and nominal FC power, or other similar considerations can help to avoid facing these situations.

5. Simulation and results

Parameters and relationships presented in section II are used to model a PEMFC FC stack. The stacks nominal power is 4 kW.

A 110 V lead-acid battery is used in this study. These kinds of batteries are employed in many electrical systems to store or deliver energy. There have been many proposals for lead-acid battery models. A comprehensive electrical circuit model for lead-acid batteries was proposed in [12]. This model can be simplified to the circuit shown in Figure 6 [13].

Figure 6: Simplified model for lead-acid batteries



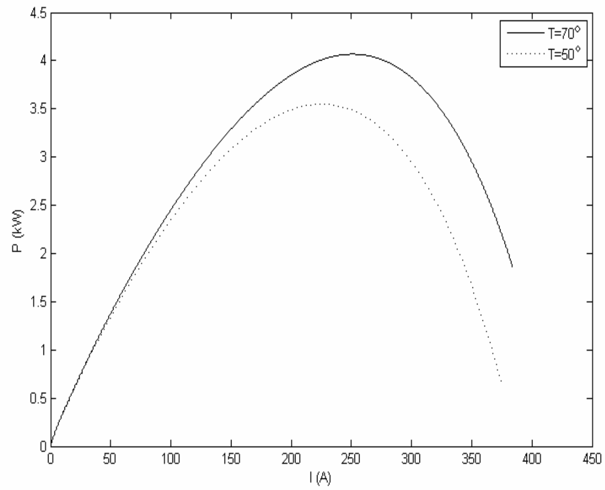
In this circuit model, C_b is battery capacitance, R_s is self-discharge resistance, R_i is internal resistance, C_o is overvoltage capacitance, and R_o is overvoltage resistance. Battery is considered fully charged before the application of load, and its charge limits are 20% and 100%.

For power electronics intermediates, Buck-Boost DC-DC converters are employed. State-space averaged model can be used to analyze the converters performance. These models can represent the average behavior of converters in steady state as well as in transients [14].

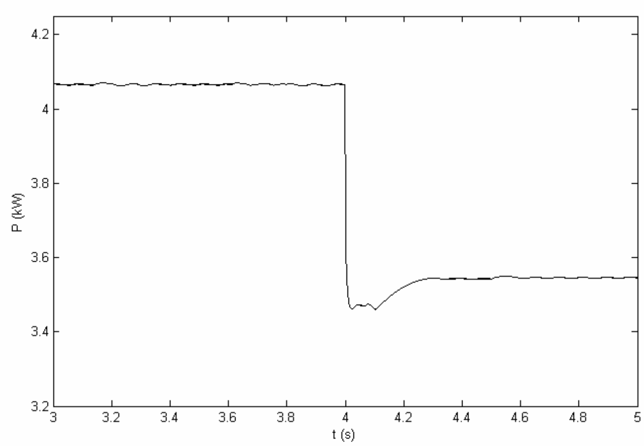
In order to analyze the performance of the proposed configuration, the system is tested and analyzed in two stages. At first, system is encountered a variable FC condition. At next step, supposing constant parameters for FC, the system is analyzed.

A hypothetical step change in FC operating temperature, T, is applied to provide a variable FC operating condition. The step change is from 70º to 50º. FC P-I curve for these two temperatures is depicted in figure 7-a. The FC output power and the output voltage of system are shown in Figure 7-b and 7-c respectively. The battery voltage is depicted in Figure 7-d. As it can be seen, the MPP of FC in different conditions is traced continuously, and operation of FC is fixed in this point. Moreover, the output voltage is regulated satisfactorily and kept constant.

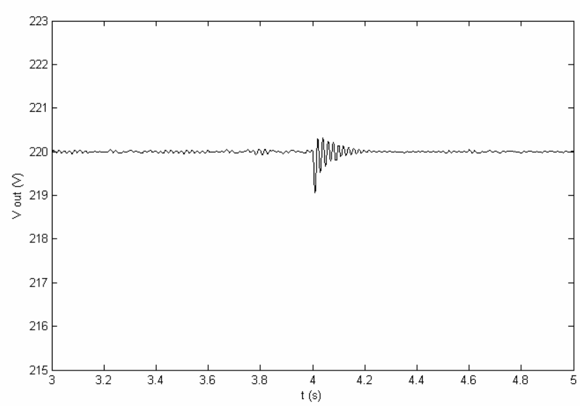
Figure 7: System performance under variable FC condition: a) FC P-I curve for two different temperatures; b) FC output power; c) system output voltage; d) battery voltage



(a)



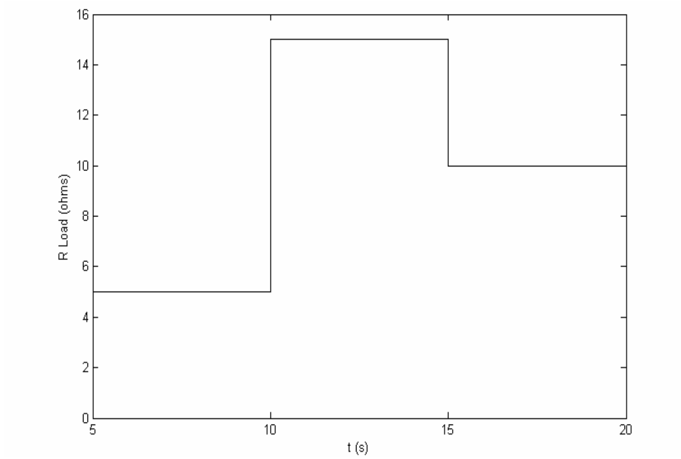
(b)



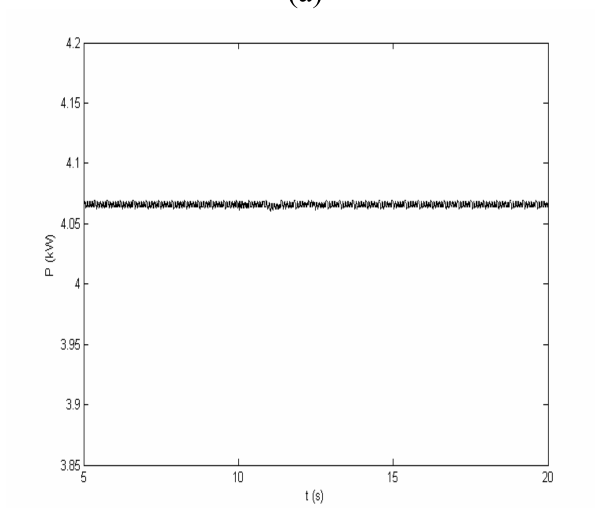
(c)

Now, effects of load resistance changes on system performance will be analyzed, supposing constant operating parameters for FC. To achieve this, FC operates in conditions which correspond to figure 1 and step changes are applied in load resistance, as depicted in figure 8-a. FC output power is represented in figure 8-b and as can be seen, in spite of wide range changes of load resistance, MPP is followed accurately and continuously. Figures 8-c and 8-d show the system output and battery terminal voltages, respectively. Again, system output voltage is kept constant in its reference value, i.e. 220 volts, as was in previous test.

Figure 8: System performance in presence of load step changes: a) step changes of load resistance; b) FC output power; c) system output voltage; d) battery voltage



(a)



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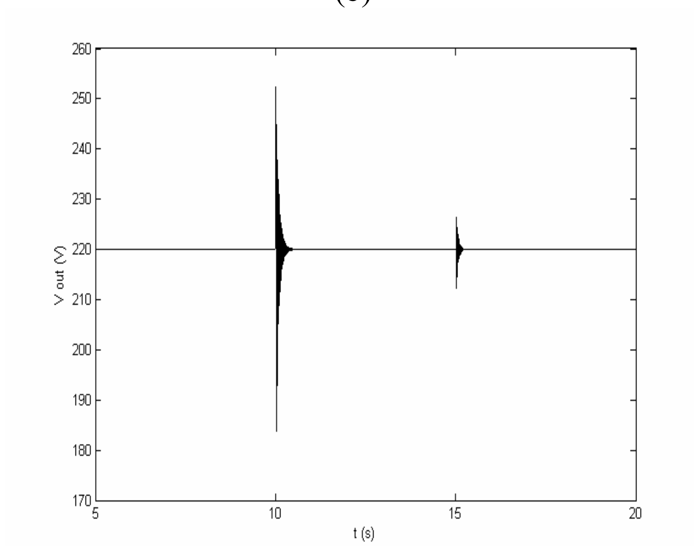
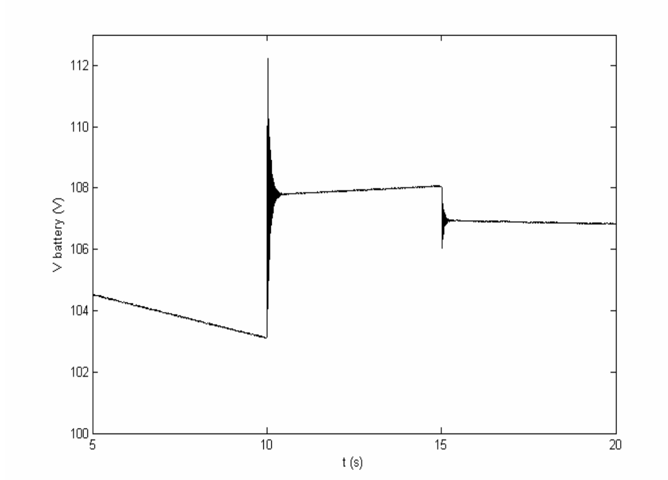


(c)



(d)

6. Conclusion

It is necessary to provide conditions in which FC can operate in its MPP, but as described in this paper, there are some problems. In order to overcome them, a new configuration for Fuel cell / Battery hybrid power system is proposed and analyzed. This system is able to utilize FC maximum power and regulate output voltage simultaneously, using two sets of controller. One is a DC-DC converter in addition to a MPPT controller, which uses P&O algorithm to trace MPP. The next is a voltage regulating controller and another DC-DC converter.

The proposed system is simulated in different conditions, and the results demonstrate appropriate performance of the system and controllers.

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