연료전지의 진단 및 부하 평준화를 위한 다중 컨버터 시스템의 설계

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Design of the Multi-converter System for Fuel Cell Diagnosis and Load Leveling

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ABSTRACT

In this research, a novel multi-converter system for the fuel cell diagnostics and the load leveling function under varying load condition is proposed. The proposed system is composed of two converters and operates in two different modes. In the normal mode operation the additional bidirectional converter is used for the load leveling and in the diagnostic mode it is used for implementing integral diagnostics by way of electrochemical impedance spectroscopy (EIS). The proposed method can perform the EIS for fuel cell under varying load conditions with no influence to the load. The validity and feasibility of the proposed system is verified by the experiments and the design procedure of the proposed system is detailed.

1. Introduction

Though the fuel cells are emerging as a viable energy source in the near future, its proliferation is delayed by the two main drawbacks of it, the limited overload handling capability and unknown lifetime. Thus the power conditioning system for the fuel cell needs to be designed to compensate for those drawbacks, thereby making the fuel cell as a reliable power source.

It is well known that the limited overload handling capability of the fuel cell can be overcome by using the hybrid topology with the energy storage device. If the battery is used as an auxiliary energy source, the system can provide the stable operation under the varying load condition and instantaneous overload condition. Unknown lifetime is another concern of the fuel cell power system. As is also well known that the fuel cell degrades as the operation hour is accumulated and eventually reaches to the end-of-life (EOD). However, since it depends on the many factors such as operating condition, load pattern and etc., sometimes it may fail suddenly. Hence, it is important to detect the aging of the fuel cell and to prognosticate its EOD, thereby preventing the sudden failure of the fuel cell power system. The electrochemical impedance spectroscopy (EIS) can be a useful tool for the diagnosis and prognosis of the fuel cell since it helps characterize the electrochemical performance and investigate the fundamental processes of the fuel cell, hence the state of health (SOH) of it.

In this research, a novel multi-converter system for the fuel cell diagnostics and the load leveling function under varying load condition is proposed. The proposed system is composed of two converters, a main converter to supply the fuel cell power to the load and a bidirectional converter for load leveling and diagnosis function. In the normal mode operation the additional bidirectional converter is used for the load leveling with the associated auxiliary battery and in the diagnostic mode it is used for implementing the integral diagnostics function by way of electrochemical impedance spectroscopy (EIS). The EIS function is implemented by generating a small current perturbation by the current controller of the boost converter and the impedance spectrum is calculated by means of the digital lock-in amplifier (DLIA) embedded in the DSP.

2. Proposed multi-converter system for fuel cell diagnostics and load leveling

Fig.1 shows the block diagram of the multi-converter system with the diagnosis function for the fuel cell and load leveling function under the varying load condition. The multi-converter consists of a conventional boost converter associated with the fuel cell and a bidirectional converter associated with an auxiliary battery. In the normal operation mode, the boost converter regulates the load voltage at the desired value and the bidirectional converter is used for handling the abrupt load change or an instantaneous overload. The idea of load leveling is to compensate the load power with power from the auxiliary energy storage device if the power from fuel cell is insufficient for supplying the full load. If the power from the fuel cell is larger than the required power for the load, the surplus power is then used to charge the battery. In the diagnostic mode, the boost converter performs the input current control to generate the frequency-swept current perturbation for the EIS operation and the bidirectional converter regulates the output voltage. It should be noticed that during the EIS mode the operation of the boost converter has to be decoupled from that of the bidirectional converter to ensure the successful impedance measurements regardless of the load variation. Thus, in this mode, the boost converter draws a small ac perturbation current over the frequency range of interests superimposed on a certain DC offset value and the bidirectional converter regulates the load voltage by charging and discharging the battery associated with it.

When the fuel cell is perturbed by a small sinusoidal current, its voltage response with respect to the current perturbation is then measured over the frequency range of interests. The Digital Lock-In Amplifier (DLIA) embedded in the DSP is used to calculate the in-phase and quadrature-phase components of the current perturbation and its voltage response, and the ac impedance of the fuel cell at each frequency can be calculated. The equivalent circuit parameters of the fuel cell are extracted from the measured impedance data by using complex nonlinear least square fitting technique. Then the extracted parameters can be used to judge the degradation and/or the SOH of the fuel cell by comparing them to the initial parameter values of the fuel cell when it was fresh.

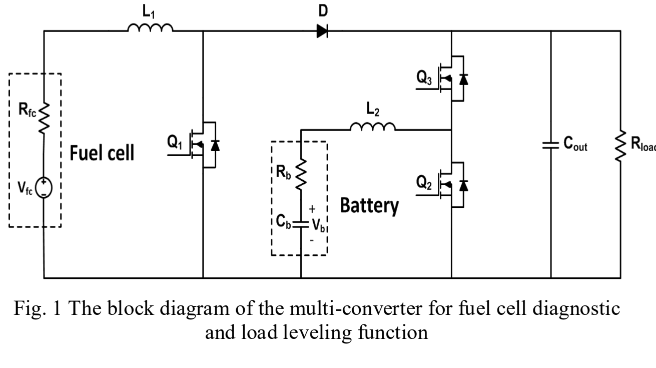

Fig. 1 The block diagram of the multi-converter for fuel cell diagnostic and load leveling function

3. Design of the voltage and current controllers for the multi-converter

The small-signal modeling technique is used to obtain the transfer function of the converters. Here, a voltage source in series with a resistor is used as the fuel cell model and an R-C circuit is used as the battery model. The control to output voltage (G_{vd1}), the control to fuel cell current (G_{id}) transfer functions of the boost converter and the control to output voltage (G_{vd2}) transfer function of the bidirectional converter can be obtained as followings.

$$G_{vd1}(s)=\frac{-sI_{L1}L_1+(1-D)V_o+R_{fc}I_{L1}}{s^2L_1RC+s(L_1+CR_{fc}R)+R(1-D)^2+R_{fc}} \quad (1)$$

$$G_{id}(s)=\frac{sV_oCR+(1-D)I_LR+V_o}{s^2LRC+s(L+CR_{fc}R)+R(1-D)^2+R_{fc}} \quad (2)$$

$$G_{vd2}(s)=\frac{-sI_{L2}L_2+(1-D)V_o+R_{fc}I_{L2}}{s^2L_2RC+s(L_2+CR_{fc}R)+R(1-D)^2+R_{fc}} \quad (3)$$

Since the transfer functions of the boost converter and the bidirectional converter operating in the boost mode both include right half-plane zeros (RHPZ), it is recommended to select the crossover frequency of the voltage loop less than one-third of the RHPZ frequencies. In this case, the RHPZ frequencies of G_{vd1} and G_{vd2} are 4.0 [kHz] and 1.2 [kHz], therefore the crossover frequencies are selected at 1.0 [kHz] and 300 [Hz], respectively. The Type 3 controllers are selected for the voltage controller due to the requirement for the phase boost.

In the design of the current controller for the fuel cell, the selection of the crossover frequency is important because the perturbation should not be distorted for the accurate impedance measurements. Since the impedance measurements need to be performed from 0.1 [Hz] to 1 [kHz] to get the useful impedance spectrum, the bandwidth of the closed-loop system should be selected ten times higher than the highest frequency of measurements in order to avoid the distortion. Thus, the bandwidth of the current loop is selected at 10.0 [kHz] in this case. The control to output current and voltage transfer functions were obtained with the following parameters: V_{fc} = 8.4 [V]; V_b = 3.7 [V]; D = 0.33; L_1 = 220.0 [μH]; L_2 = 170.0 [μH]; C_{out} = 220.0 [μF]; C_b = 40000.0 [F] and R_b = 30.0 [mΩ]. Finally, the voltage controllers and the current controller for the multi-converter were designed as followings:

$$G_{typ3\_1}(s)=\frac{3.865\times10^{-8}s^2+5.134\times10^{-5}s+0.017}{4.237\times10^{-13}s^3+5.038\times10^{-5}s^2+0.0015s} \quad (4)$$

$$G_{typ3\_2}(s)=\frac{1.297\times10^{-7}s^2+9.27\times10^{-5}s+0.017}{2.289\times10^{-13}s^3+5.058\times10^{-5}s^2+0.0028s} \quad (5)$$

$$G_{pi\_c}(s)=\frac{1.13s+2420}{s} \quad (6)$$

4. Experimental result

Fig. 2 shows the operation of the proposed multi-converter system during normal mode operation and EIS mode operation for the fuel cell. It is clearly seen in the Fig. 2 that the load voltage is regulated at 12 [V] in both normal mode operation and EIS mode operation. Since the current perturbation generated for the EIS is absorbed by the auxiliary battery associated with the bidirectional converter, there is no intervention between the EIS operation and the output voltage regulation. Fig. 3 shows the operation of the multi-converter system under varying load conditions. As shown in the Fig. 3, the output of the converter is regulated at 12V precisely during the EIS operation while the load is varying randomly, since the bidirectional converter compensates for it by charging/discharging the battery.

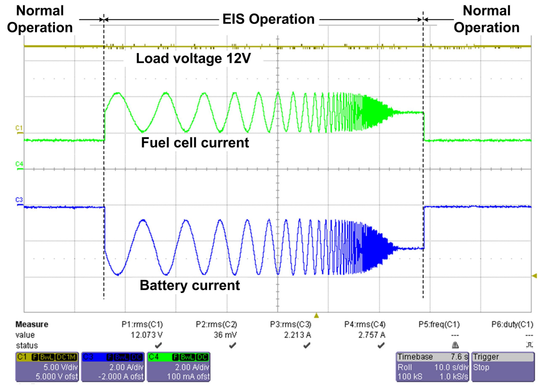

Fig. 2. Load voltage, fuel cell current and battery current waveforms during the normal operation and EIS operation of the proposed system

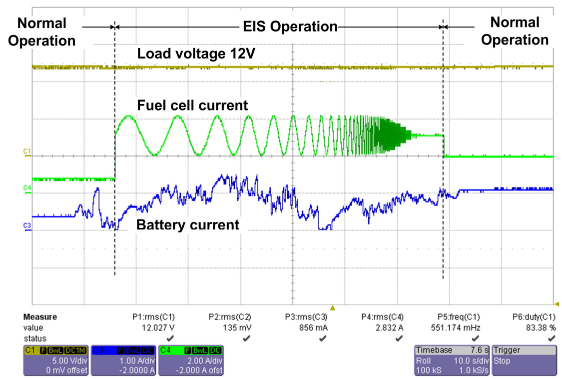

Fig. 3. Load voltage and fuel cell current waveforms under varying load conditions

The impedance spectrum of the fuel cell obtained by the proposed system is then verified by comparing with the results obtained by the WEIS500 electrochemical workstation as shown in the Fig. 4.

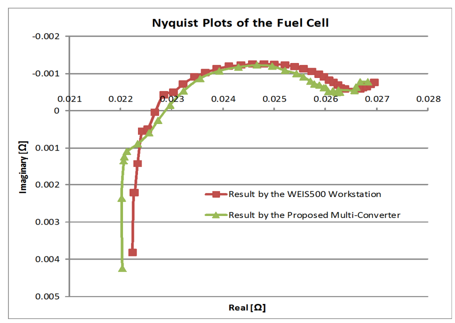

Fig. 4. Nyquist impedance plots of the fuel cell

5. Conclusion and Future Work

A novel multi-converter for fuel cell diagnosis and load leveling function has been proposed. The impedance spectrum of the fuel cell was measured successfully by the proposed multi-converter even under the varying load condition. The proposed system can be used to prognosticate the SOH of the fuel cell during the operation with no influence to the load.

Reference

[1] John J. Cooley, Peter Lindahl, Clarissa L. Zimmerman, Matthew Cornachione, Grant Jordan, Steven R. Shaw and Steven B. Leeb, "Multi-converter System Design for Fuel Cell Buffering and Diagnostics under UAV Load Profiles", IEEE Transactions on Power Electronics, Issue 99, 2013.