Electronic Circuit Models and Dynamic Transient Phenomena of a Proton Exchange Membrane Fuel cell-A Review

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The proton exchange membrane fuel cell (PEMFC) is being utilized by more and more researchers in new renewable energy studies. And the internal construction of PEMFC behaves much like an electrical capacitor which has the dynamic transient phenomena of voltage and current. And they are critical to the applications which use the PEMFC as the power source. In this paper the recent works on the electronic circuit models for PEMFC and the simulations as well as experiments of PEMFC dynamic transient phenomena are reviewed.

1. Introduction

The concept of hydrogen fuel cell was firstly introduced by Sir William Robert Grove more than 150 years ago and then developed by Ludwig Mond, Charles Langer, Friedrich Wilhelm Ostwald in 19th century. In 20th century, the leading researchers pushed the fuel cell concept to its adolescence and many successful implementations were developed. Nowadays, as we can see, the number of different applications of fuel cell is very extensive and there is an increasing interest in fuel cell technology and fuel cell will reach a high development status [1].

As a kind of power sources, fuel cell can meet or supply the heat and electric power needs. It is a unique solution to diminishing supplies of fossil fuel, environmental pollution, and global warming. And because fuel cell has benefits include high efficiency and reliability, multi-fuel capability, siting flexibility, durability, scalability and ease of maintenance. There are a wide range of applications like auxiliary units, distributed power generation, residential combined heat and power generation system, transportation applications and portable applications, especially in remote locations, such as spacecrafts, remote weather stations, parks, rural locations, and in certain military applications [2, 3].

2. The proton exchange membrane fuel cell (PEMFC)

Generally, there are five major types of fuel cells, differentiated from one another on the basis of their electrolyte type: phosphoric acid fuel cell (PAFC), proton exchange membrane or polymer (electrolyte membrane) fuel cell (PEMFC), Alkaline fuel cell (AFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC). Besides, there are many other fuel cells that represent variants of the standard types or do not easily fall into the typical classification. These nonstandard fuel cell types include direct liquid-fueled fuel cells, biological fuel cells, membraneless fuel cells, metal-air cells, single-chamber SOFC, direct flame SOFC, liquid-tin anode SOFC [2, 3].

Although different types of fuel cells have been developed, PEM fuel cells are well suited for many applications including automobiles, buildings, and for smaller applications. PEM fuel cells have gained international attention as candidates for alternative automotive and stationary power sources due to features such as their highest power density of all the fuel cell classes, good start-stop capabilities, adaptable size and low operating temperatures [2-4].

Polymeric membrane technology was invented by the company GE with the work of T. Grubb and L. Niedrach. The proton exchange membrane (PEM) fuel cell is very simple and is constructed from a proton-conducting polymer electrolyte membrane, usually a perfluorinated sulfonic acid polymer [1]. Fig.1 is the rendering of the 2005 Honda FCX fuel cell car power train. Two PEMFC stacks generate 86 kW of electricity.

PEMFC combines hydrogen and oxygen over a platinum catalyst to produce electrochemical energy with heat and water as the byproduct [5]. In a fuel cell, hydrogen is fed at the anode, oxygen is fed at the cathode, and an electrolyte is sandwiched between the two electrodes for conveying ion e- from the anode to the cathode [2]. Fig.2 shows the operating principle of PEMFC. The anode and cathode reactions in the PEMFC are H

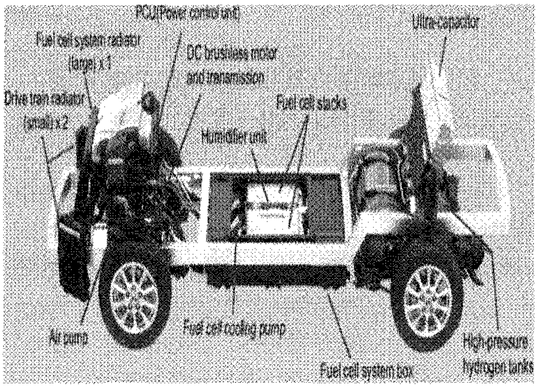

Fig. 1. Rendering of the 2005 Honda FCX fuel cell car power train [3].

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

Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ [3]

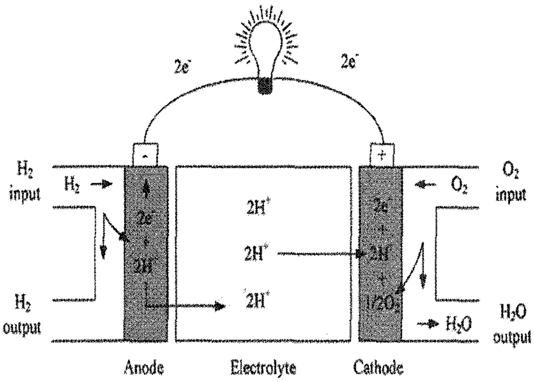

Fig. 2. PEMFC principles of operation [1].

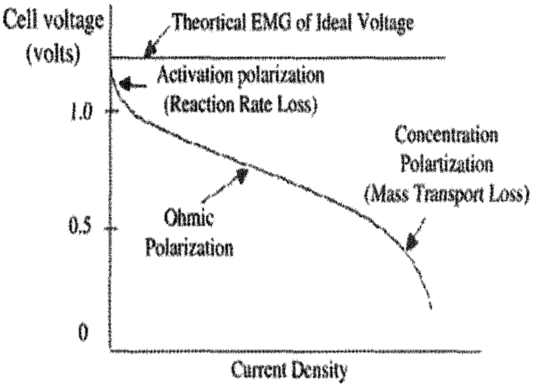

Fig. 3. The typical V-I characteristic polarization curve of a PEMFC at room temperature and normal air pressure [5].

Fig. 3 shows the typical V-I characteristic polarization curve of a hydrogen-oxygen polymer electrolyte membrane fuel cell at room temperature and normal air pressure [5]. The three operating ranges are identified as the activation polarization region, the ohmic polarization region and the concentration (mass transport) polarization region.

3. Electronic circuit models for PEMFC

From the PEMFC V-I characteristic polarization curve, it can be deduced that the PEMFC has dynamic characteristics. So there is a need to design the electronic circuit models of the PEMFC to make the fuel cell operation simpler and it is easier to understand PEMFC' s dynamic characteristics performance such as the transient response of PEMFC. The electronic circuit models for PEMFC include the following:

Jay B. Benziger, M. Barclay Satterfield, Warren H.J. Hogarth addressed the PEMFC is appropriate to describe as a battery. A single fuel cell, with uniform gas compositions at both the anode and the cathode, may be represented as a set of three circuit elements as shown in Fig. 4. The voltage of the power source is V_b, R_m presents the internal membrane electrolyte resistance. Because of the diode, the parameters include saturation current I_0 and threshold voltage V_T. The external load resistance R_L is the manipulated parameter. The current through the load resistance is described as i and V is the voltage across the load resistance [6].

Dachuan Yu, S. Yuvarajan demonstrated a proposed circuit model of a commercial PEMFC module which is showed in Fig.5. In Fig.5, the circuit is composed of two BJTs Q_1, Q_2 and the current sensing resistor R_2. When the current through R_2 exceeds a set limit, Q_2 starts conducting and reduces the base voltage of Q_1 [5].

Because the PEMFC has the diffusion effects and the reactions between the electrons and the ions, and the layer of charge on or near the electrode interface behaves much like an electrical capacitor, many researchers considered it is quite reasonable to use a capacitor to model the PEMFC.

P.R. Pathapati, X. Xue, J. Tang attempted to represent the charge double layer by an electrical capacitor. The equivalent model of PEMFC is showed in Fig. 6, the dynamics of fuel cell voltage

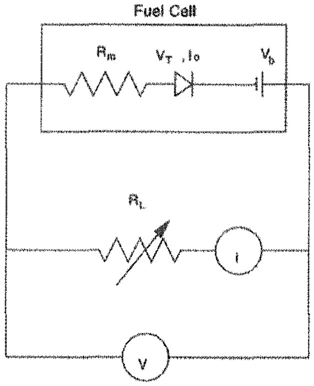

Fig. 4. Equivalent circuit for a PEMFC.

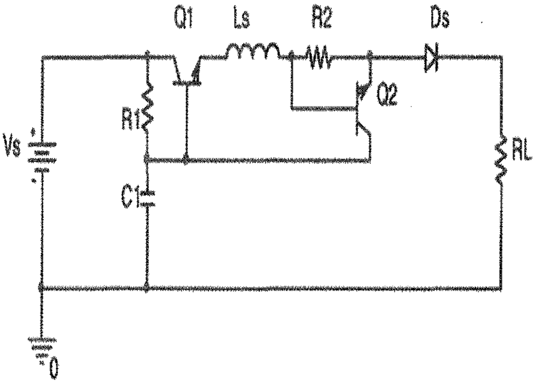

Fig. 5. Proposed circuit model for PEMFC module.

can be captured based on the equivalent model [7].

HUA Jianfeng, XU Liangfei, LIN Xinfan, LU Languang and OUYANG Minggao investigated the method which was described in Fig. 6 leads to unsatisfactory curve fitting results. Their approach to the equivalent circuit model leads to a fit with a slope too steep to fit the voltage curve in the beginning and not steep enough at the end of the voltage response curve. So they integrated an additional RC-element in series in the circuit as shown in Fig.7 [8].

Ciureanu and Roberge proposed a kind of equivalent circuit used to model the impedance spectra and it is showed in Fig. 8. The two parallel combinations of a resistance and a constant phase element (CPE) represent the charge transfer processes in the anode and cathode. CPEs are used instead of capacitances since measured impedance spectra contained depressed semi-circles, which are typical for porous electrodes [9].

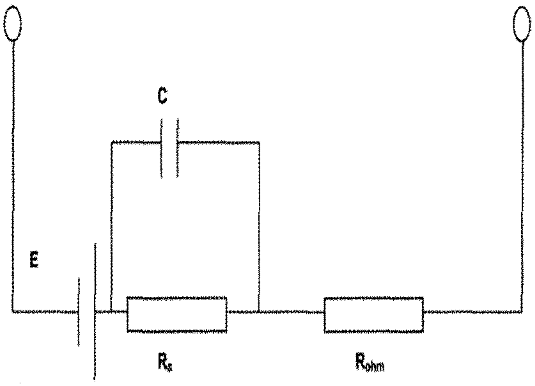

Fig. 6. Equivalent model for PEMFC.

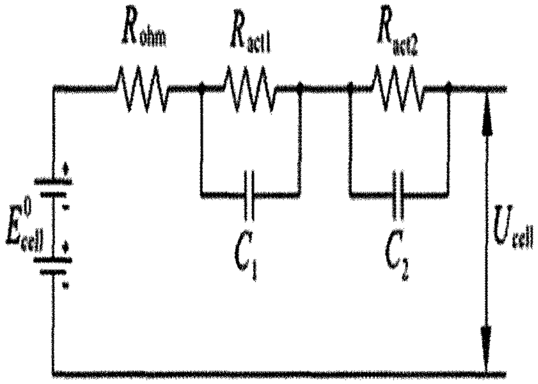

Fig. 7. Additional RC-element in the equivalent series model.

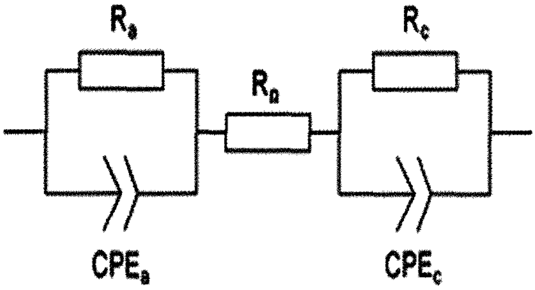

Fig. 8. Equivalent circuit for PEMFC.

4. Transient Phenomena

Because the internal construction of PEMFC behaves much like an electrical capacitor, if the current changes, it will take certain period for this charge to build up or dissipate. Therefore, the voltage (activation) does not immediately follow the current like the general ohm I-V characteristics, but moves fairly slowly to its final equilibrium value. And if the PEMFC supply power to certain applications such as vehicles which the power requirement varies rapidly, the transient response of PEMFC is critical [10].

P.R. Pathapati, X. Xue, J. Tang simulated the transient dynamic behavior of the PEMFC. As shown in Fig. 9, the fuel cell load current has been varied initially and then undershoot. In Fig. 10, when the current reduced suddenly, voltage overshoot is visible in response [7].

Tuomas Mennola, Mikko Mikkola, Matti

Noponen, Tero Hottinen, Peter Lund experimented with the commercial fuel cell module to a step change in load shows a small undershoot. In the mean time, the output current increases very quickly. It can be seen the transient performance in Fig.11. [5]

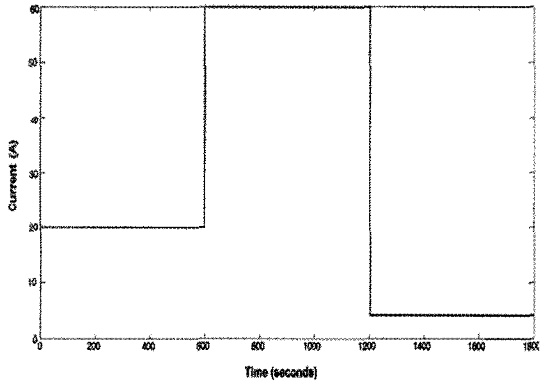

Fig. 9. Fuel cell load current vs. time.

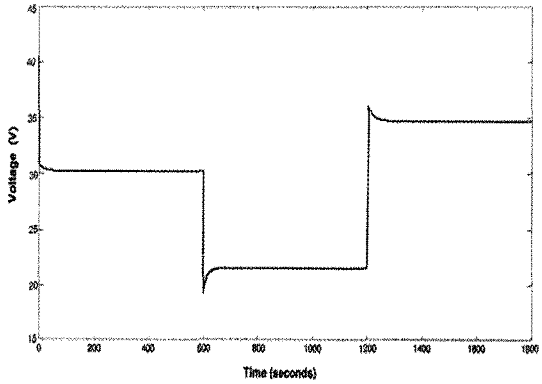

Fig. 10. Fuel cell voltage vs. time.

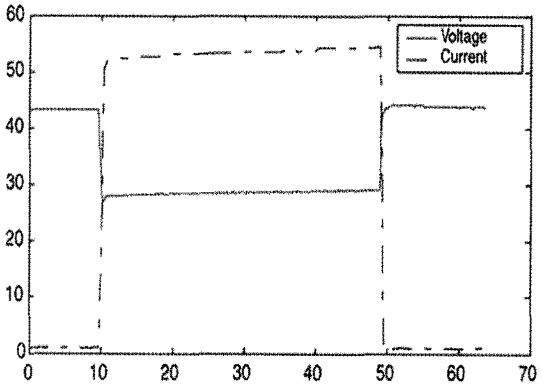

Fig. 11. Experimental waveforms of PEMFC.

Helge Weydahl, Steffen Møller-Holst, Georg Hagen, Børre Børresen studied that when the external load resistance decreases step by step, the initial response in cell voltage and current are shown in Fig. 12 and Fig. 13. Firstly, the cell voltage drops fast and then relaxes slower, finally, towards to the new steady state. Fig. 13 presents the current density that first jumps to a higher value and then

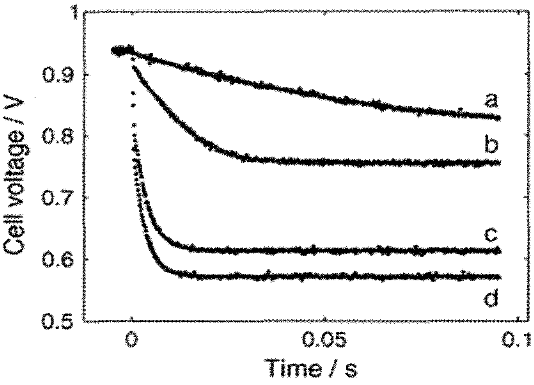

Fig. 12. First 100 ms of the transient response in cell voltage upon a step change in the external load resistance.

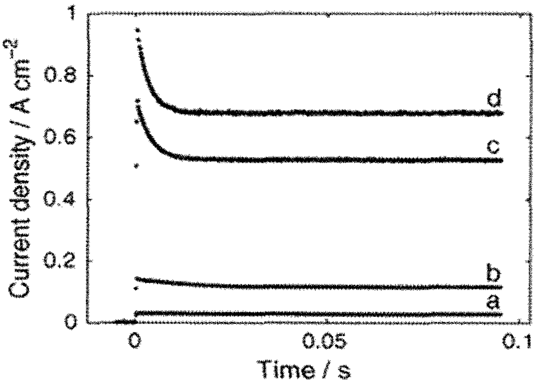

Fig. 13. First 100 ms of the transient response in current density upon a step change in the external load resistance.

decays and towards to the new steady state [9].

Tuomas Mennola, Mikko Mikkola, Matti Noponen, Tero Hottinen, Peter Lund measured the voltage transient of an individual cell, as it can be seen in Fig. 13, representing the typical features [10].

Junhyun Cho, Han-Sang Kim, Kyoungdoug Min researched the schematic of this undershoot behaviour which is illustrated in Fig. 14. When the load changes from low to high value, the voltage also reaches the new steady state at last, but they found the response includes two different time delays [11].

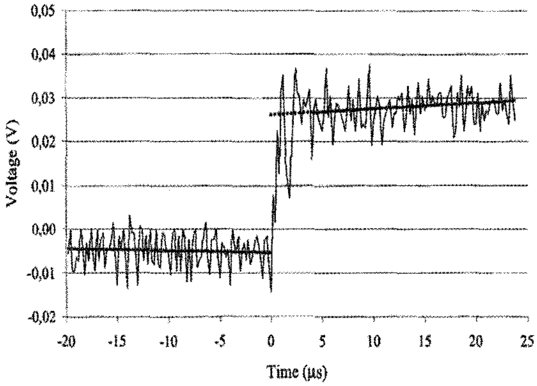

Fig. 14. Voltage transient of an individual cell.

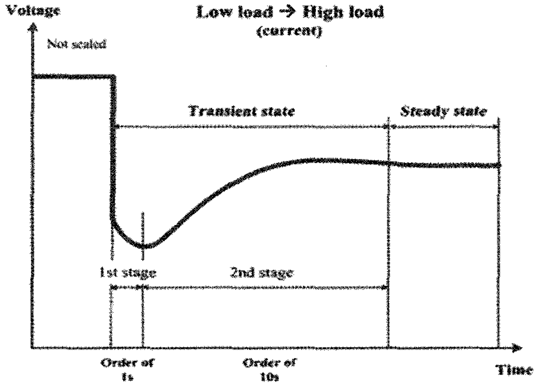

Fig. 15. Voltage undershoot's behaviour during the current step change from low value to high value.

5. Conclusion

Throughout this work we have reviewed the history and the current state of fuel cells, especially, the main point of the paper is the proton exchange membrane or polymer (electrolyte membrane) fuel cell (PEMFC). To address this part, firstly, the paper introduced the operation principles of PEMFC and illustrated the typical V-I characteristic polarization curve of a PEMFC. Then this part focuses on the equivalent model or circuit for a PEMFC which are designed by the researchers. Furthermore, according to the equivalent model or circuit, and combining with the experiments and simulations, as the results of experiments and simulations, the dynamic transient phenomena are illustrated and listed in this paper.

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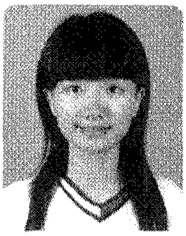

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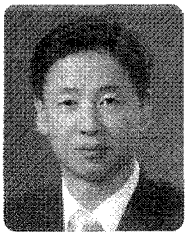

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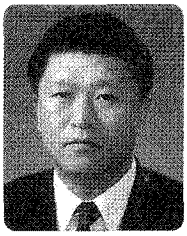

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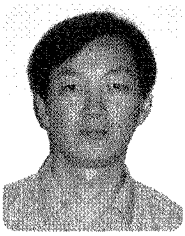

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