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Andreasen, Søren Juhl; Jespersen, Jesper Lebæk; Kær, Søren Knudsen

Publication date: 2008

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Modelling of a High Temperature PEM Fuel Cell Stack Using Electrochemical Impedance Spectroscopy

Søren Juhl Andreasen*, Jesper Lebaek Jespersen, Erik Schaltz, Søren Knudsen Kær

Department of Energy Technology, Aalborg University, Pontoppidanstræde 101, 9220 Aalborg East, Denmark

Motivation

In designing and controlling fuel cell systems it is advantageous having models predicting the behavior of the fuel cells in steady-state as well as in dynamic operation. This work examines the use of electro-chemical impedance spectroscopy (EIS) for characterizing and developing a model for a high temperature PEM (HTPEM) fuel cell stack. A Labview virtual interface has been developed to perform the signal generation and acquisition which is needed to perform EIS. The typical output of an EIS measurement on a fuel cell, is a Nyquist plot, which shows the imaginary and real part of the impedance of the measured object. A typical Nyquist plot of a typical equivalent electric circuit of fuel cell is shown in figure 1.

HTPEM Fuel Cell Stack Electrochemical Impedance Spectroscopy

The fuel cell stack tested in this work is a 65 cell 1 kW HTPEM fuel cell stack using a polybenzimidazole (PBI) membrane doped with phosphoric acid to increase the proton conductive abilities of the membrane. The HTPEM fuel cell stack is fuelled with pure hydrogen in a dead-end anode configuration at a constant pressure of 0.2 bar. The air to the cathode is supplied by a low power axial blower, which also is used to control the stack temperature. The temperature control is realized by a feed forward of the current and a feedback of the measured stack temperature. Figure 3 shows the fuel cell system setup, and components in the system.

The Labview based program controls the I/O from a PCI 6259 Multifunction DAQ. The board controls a 16 bit 0-10V analog output signal as a Nyquist plot, which shows the imaginary and real part of the impedance of the measured object. A typical Nyquist plot of a typical equivalent electric circuit of fuel cell is shown in figure 1. The fuel cell stack setup is shown in figure 2. The fuel cell voltages can be measured in different places to examine the impact of fuel cell stacking.

The developed software is able to include multiple of the simultaneously measured current and voltages in the signal conditioning using the same stack current.

Nyquist plots made using measurements of the presented system are shown in figure 5 and 6. In figure 5 and 6 Nyquist plots of the fuel cell stack impedance is shown at a 9 A and 15 A DC offset current and at different stack temperatures. The choice of the DC current offsets is within the linear operating point on stack polarization curve. The measured Nyquist plots show similar behavior to the equivalent circuit model shown in figure 1, with a large cathode semi circle in the low frequency range, and a small anode semi circle in the high frequency range. The measurements show that both the real and imaginary parts decrease with increasing temperatures, i.e. the electrical dynamic performance is better at higher temperatures. This is also expected, while the speed of the chemical processes occurring typically speed up at higher temperatures. In the case of a fuel cell stack impedance compared to a single cell impedance, the stack consists of many series connected fuel cells with varying temperatures and therefore also impedances. This could be one explanation of why there is not a clear distinction between the two semi circles in the measurements. Results from these measurements are much similar.

Modelling

The impedance of a stack of series connected fuel cells resemble that of a single cell, although the different temperatures can make it difficult to determine the exact sizes of the cathode and anode equivalent circuits. Figure 7 shows measurements on the same system of base with a Gamry FC390 Fuel Cell Monitor to verify the results from the developed Labview program.

Using an equivalent model for the entire stack, as the one shown in figure 1, with $R_a=0.045Ω$, $C_a=0.05F$, $R_c=0.56Ω$, $C_c=0.3F$, and $R_o=0.26Ω$, yields the Nyquist also shown in figure 7. It is seen that the plot has a too high capacitive impact compared to the experimental results. The fuel cells do in this case not behave strictly as standard electrical components, so to get a better model representation the cathode capacitor is substituted by a constant phase element with $\theta=0.85$. The resultant model predicts the behaviour of the fuel cells much better.

Conclusions

The experimental results presented suggest that the developed Labview software is capable of making a frequency scan of the fuel cell current and voltage, resulting in a Nyquist plot showing the impedance of the fuel cell stack. A simple equivalent circuit model can be used to simulate the fuel cell stack behaviour, but the impedance is non-linear and depends on other variables such as for example temperature.

Future work with this fuel cell stack includes measuring the impedance at different hydrogen pressures and cathode stoichiometries. To further characterize the anode part of the fuel cell stack, measurements with different CO concentrations in the supplied hydrogen should be made. Single cell measurements should also be carried out to analyze the impact on the impedance when stacking the fuel cells.