# Equivalent Circuit Models for Polymer Electrolyte Fuel Cell Stacks in Parallel at Operational Loads

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Two PEFC stacks were first tested individually at a level up to 1 kW stack power with and without the embedded control devices, and then ac impedance measurements were conducted after the system reached a steady state. The two stacks containing 47 MEA cells each were connected in parallel using room air and pure hydrogen fuel supply (purity > 99.99%). Next, *ac* impedance evaluations were conducted after the stacks reached a steady state at a certain power level. The equivalent circuit model of the PEFC system in testing is developed through the real time data and non-linear least squares fitting. Data interpretation for the simulated elements was given according to the physical phenomenon and electrochemical reactions. The two PEFC stacks were then tested for pulse capabilities at different current levels. The physical elements in the equivalent circuit model were programmed into a PSpice tool for electronic pulse simulation. The tested data from the digital oscilloscope are in satisfactory agreement with the results from PSpice simulation.

**Keywords**: fuel cell stack characterization; *ac* impedance; stack diagnosis, stack parallel operation; proton exchange membrane fuel cells.

Electrochemical impedance spectroscopy (EIS) is a powerful electrochemical technique to analyze the kinetics of electrode reactions. The advantage of this steady-state technique is the capability of probing relaxation phenomena over a wide frequency range [1]. During EIS tests, a small *ac* signal usually between 5 mV and 10 mV per cell is applied to the electrical circuit. Excitation waveforms of this *ac* amplitude cause minimal perturbation of the electrochemical test system assuring linearity between the output and input signals. This pseudo-linearity of the current and the potential differences makes it possible to treat the electrode system as a linear electrical circuit. Therefore, the application of the equivalent electrical circuit becomes the major technique to analyze the EIS data using different computer-fitting programs. Quantitative fittings through different electrical circuits are difficult to find a proper physical equivalent for matching the test data. This is caused by the complexities of a real electrochemical system. However, simple or more complicated equivalent circuit models can be developed and have good approximations to the real systems. Test data can be fitted to yield results of reasonable accuracy. This work describes the initial equivalent circuit model developed for the PEFC stacks operated in parallel at loads.

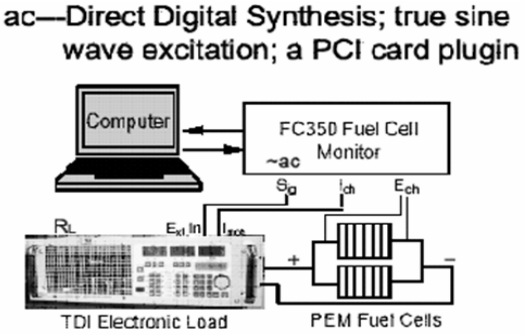


**Figure 1.** Two Ballard Nexa™ PEFC stacks connected in parallel operation for *ac* impedance measurement.

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The Ballard PEFC stacks (#515 and #881) in the Nexa™ system are a small fuel cell system providing 1200 watts of unregulated DC power at a nominal output voltage of 26 Vdc. Its open circuit voltage is *ca.* 41 volts at room temperature. Two of these stacks in systems were connected and operated in parallel. A Gamry FC350™ fuel cell monitor with a TDI electric load is capable of measuring the impedance of operating fuel cells at high current levels. The sinusoidal current signal from the FC350, working in galvanostatic/hybrid impedance mode, modulates the current from single or multiple fuel cell(s) or the PEFC stack. Simultaneously, the current information at the electric load is sent to the FC350™ monitor. The fuel cell voltage is measured by the FC350 directly. The FC350 collects these data and generates the impedance. For two stacks operating in parallel, the basic wiring circuit diagram is described in Figure 1. The measurement of current and voltage at a given frequency allows the calculation of the fuel cell impedance parameters. The Gamry hybrid EIS mode was applied for the experiments in order to observe the EIS behavior at low frequencies, and the 150 mV *ac* voltage was normally employed for the stack tests. For the single stack in the Nexa™ system, it was tested with and without the embedded controller. For the stack characterization in parallel using the *ac* impedance technique, the power for the system controller is supplied by the fuel cell stack itself, and this controller was not separated from the PEFC system. The Gamry Echem Analyst software was applied to simulate the *ac* impedance data for stacks operating in parallel.

Two PEFC stacks in Nexa™ power module were arranged in parallel with relay switches and diodes. The TDI electronic load was applied in a constant current mode. After two stacks were running at a steady state (temperature maintains at a constant value), the Gamry instrument was started applying the *ac* excitation to the current loaded circuit. The Nyquist plot of the measured impedance

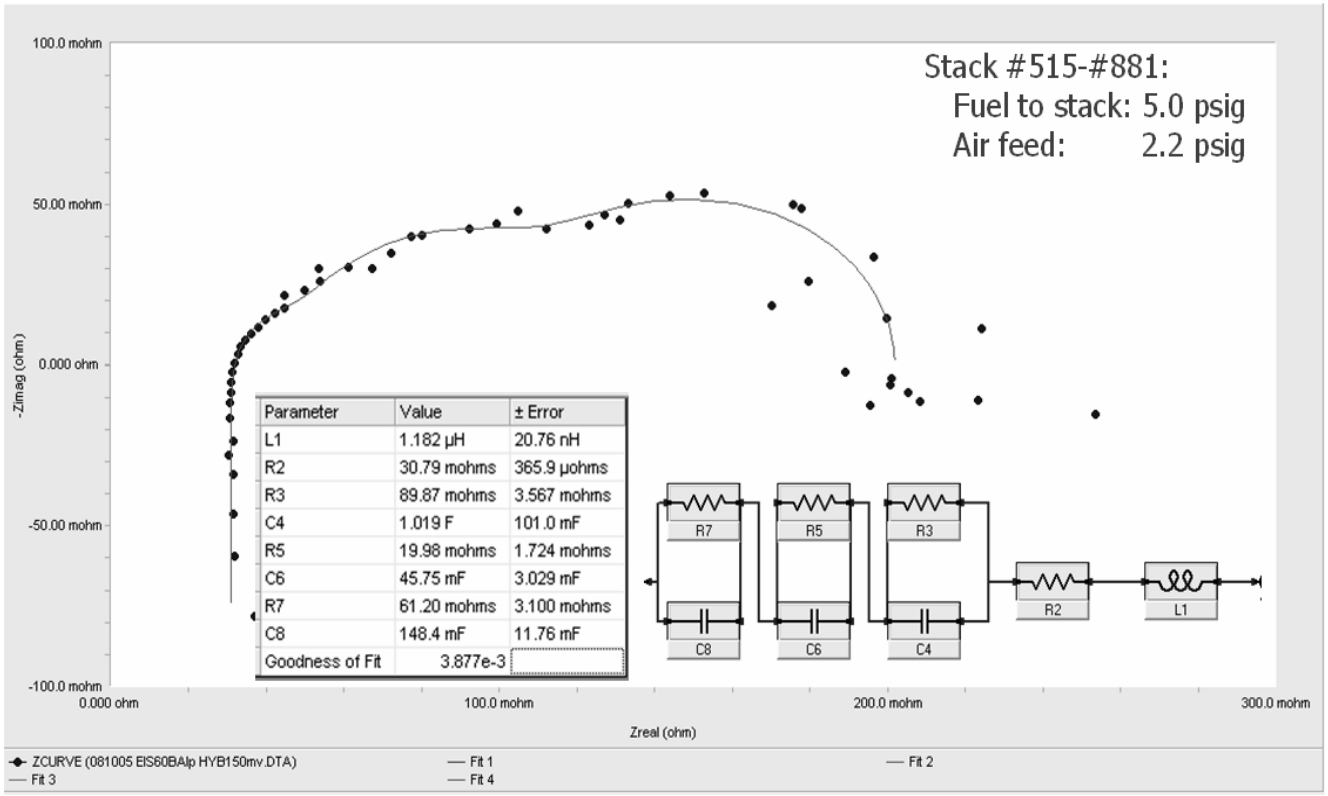


**Figure 2**. Nyquist plot, equivalent circuit diagram, and simulated physical elements of two Ballard Nexa™ stacks in parallel operation using a LR(RC)(RC)(RC) circuit fit at a load of 60 A.

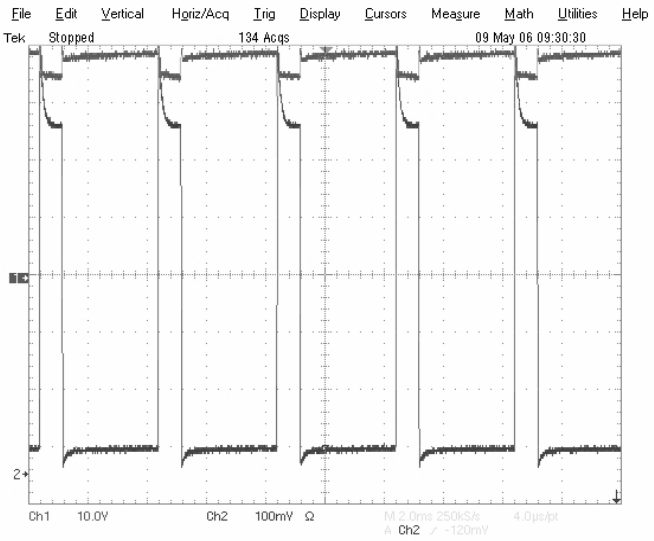


**Figure 3**. Two Nexa™ stacks (#881 and #515) operated in parallel and pulse tested at a total current (bottom line) of 60 A and pulse voltage (top line) between 35.4 V and 39.4 V at 250 Hz frequency and 20% duty cycle. Before tests at 60 A, Nexa™ stack #881: Ts=54.5°C, Es=31.36 V, Is=29.45 A, Ps=925 W; Stack #515: Ts=60.6°C, Es= 31.66 V, Is=36.47 A, Ps=1155 W.

spectrum at a 60 A current load is shown in Figure 2. From the measured spectrum, it is clearly shown that there are three semicircles (three RC time constants) in the measured impedance spectrum. So the equivalent circuit LR(RC)(RC)(RC) is employed to simulate and fit the spectrum. The fitting curve from the equivalent circuit model is well matched with the measured impedance spectrum. The physical elements and related processes can be interpreted through the Gamry simulator with the above 3-RC circuit model. One (RC) unit is contributed by the Nernst impedance [2], which is related to the diffusion step in the backing layer (*i.e.* mass transport process or concentration losses in the fuel cell cathodes) at a higher power output level. Basically, the equivalent circuit model is a reasonable simulation for the real physical processes mostly occurring in the parallel operating stacks, if valuable information can be extracted from the circuit elements and reasonable explanation can be given to the circuit model. Here the simulated model is the overall behavior of all fuel cells in two parallel stacks. Individual behavior of the fuel cell located at the exhaust outlet may have different processes. It is not considered and may be over shadowed by large number of other common processes in the whole fuel cell reactions.

As shown in Fig.2, the capacitor acts as a short circuit at the high frequency side ($f\rightarrow\infty$), and only the series ohmic resistance remains in the circuit (mostly electrolyte resistance). The first semicircle on the left side of the spectrum reveals the anode behavior of activation kinetics. The second following semicircle is the cathode behavior of activation kinetics. The third one near to the low frequency side is the cathode behavior of mass transport limitations. At the very low frequency condition ($f\rightarrow 0$), the double layer capacitance, or the Nernst capacitance, serves as an open circuit. The resistance includes the series ohmic resistance, charge transfer resistance, and Nernst diffusion resistance that can be determined separately. After the electronic load was up to 60 A, the measured points of the impedance spectrum had a little more noise than that of the lower current operation, the fluctuation of which started at the second semicircle, *i.e.* cathode activation zone. These points were far away from the simulated curve at the high operating current. It reveals that two or more processes exist inside the cathode of the fuel cell system. One of the reasons is liquid water plugging the micropores in the back diffusion layers and reducing the mass transport capability of the cathodes. After nitrogen diffuses back or water is removed from the plugged pores, the mass transport behavior is enhanced. This process changes the mass transfer rate of the cathode air and is displayed as stray impedance points. If this explanation is reasonable, the smoothness of the curve would be enhanced by operating the system at a higher temperature to vaporize the liquid water. As a whole, the above equivalent circuit briefly describes the overall fuel cell behavior in the whole system. It can be further applied to the PSpice simulation

through the equivalent circuit.

Two Nexa$^{TM}$ stacks (#881 and #515) operated in parallel and conducted the pulse pulse test at a total current of 60 A. Before pulse tests at 60 A, the Nexa$^{TM}$ stack #881 was recorded as Ts=54.5°C, Es=31.36 V, Is=29.45 A, Ps=925 W; and the Stack #515 was recorded as Ts=60.6°C, Es=31.66 V, Is=36.47 A, Ps=1155 W. Due to the difference of the internal resistance, the power output levels reveal a difference between two stacks. The pulse voltage was measured from 35.4 V to 39.4 V at 250 Hz frequency and 20% duty cycle as shown in Figure 3.

For the Nexa$^{TM}$ PEFC stack with the embedded controller, AC impedance data were in-situ measured. The equivalent circuit model takes the cathodes, electrolytes, and anodes into account. The PSpice results are included in the coming presentation. Through the constant current load (galvanostatic method), the direct pulses was passed toward the fuel cells. The PEFC system shows a strong pulse capability at a higher current level of 60 A and a temperature of *ca.* 55-60° C in comparison with operation at lower temperatures. During pulse tests, the constant current mode was applied before pulse loads. It is not understood why there is a sharp current drop from peak to the setting point of 60 A. However, the results from the pulse equivalent circuit using AC impedance technique and PSpice A/D analog or digital simulation stimulate the real time evaluation of the PEM fuel cell(s) and give us better understanding of the physical/chemical processes in the pulse power system.

**References**


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